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The effect of cryogenic treatment on the performance of high speed steel lathe tools

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by Sankaran Ramaratnam

Abstract

An analysis of the effect of cryogenic treatment on the performance of a high speed steel lathe tool is reported herein. The average crater wear areas for different cutting conditions are measured and are used as the parameter to compare the performance criteria of the tools treated for different cryogenic heat treatments.

The test results indicate that the crater wear depends largely on the speed, feed, depth and the time of cut. In addition to this, the results indicate that the effect of cryogenic treatment also has a definite contributive effect on the performance criteria of the tools under investigation.

The cryogenic treatment increases the wear resistance property of the tool. The test results indicate that the tool which is cryogenically treated once has a better wear resistance property than one which is not treated so. And the tool which is cryogenically treated twice has a better wear resistance property than one which is cryogenically treated only once. This is because the cryogenic quenching transforms a portion of the relatively soft retained austenite in the tool specimen into a hard constituent called martensite. This transformation results in a slight increase in the hardness of the tool by a few points on the Rc scale. Also, austenite being relatively unstable has a tendency to transform into martensite due to aging, which is accompanied by an increase in volume of up to a maximum of

about four percent, resulting in residual stresses. Sometimes even a dimensional change occurs due to this. The cryogenic treatment transforms more of the austerite in the tool into martensite, which minimizes the residual stresses due to aging. Also, cryogenic treatment induces a more uniform microstructure to the tool and this uniformity of microstructure also contributes to the wear resisting property, thereby increasing the service life of the tool.

The test results also indicate that the tool with two tempering operations has a better wear resistance property than the one with one tempering operation and a cryogenic quenching. This indicates that the second tempering operation cannot be substituted by a cryogenic quenching. The second tempering operation induces secondary hardness to the tool specimen. The tool with two tempering operations and two cryogenic quenchings stands the best among the various groups tested.

THE EFFECT OF CRYOGENIC TREATMENT ON THE PERFORMANCE OF HIGH SPEED STEEL LATHE TOOLS

by
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The cryogenic treatment increases the wear resistance property of the tool. The [illegible] tool which is cryogenically treated twice has a better wear resistance property than one which is cryogenically treated only once. This is because the cryogenic quenching transforms a portion of the relatively soft retained austenite in the tool specimen into a hard constituent called martensite. This transformation results in a slight increase in the hardness of the tool by a few points on the Rc scale. Also, austenite being relatively unstable has a tendency to transform into martensite due to aging, which is accompanied by an increase in volume of up to a maximum of

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The Effect of Cryogenic Treatment on the Performance of High Speed Steel Cutting Tools

Introduction

Economy in metal machining is associated with a high rate of production of an article of acceptable dimensional accuracy and surface finish and with a long tool life. Tool wear is one of the most important factors in metal cutting operations and is a major index of the performance criteria of a cutting tool. Many investigators have attempted to correlate tool wear and/or tool life with some single parameter measurable quantity or a group of measurable quantities. The reason is more than academic. A very large sum of money is spent every year on perishable tools. Any savings that is made on these tools by increasing the tools' life will therefore have a profound effect in the overall savings in a year.

The failure of a cutting tool takes place in machining all types of metals. The wear on the cutting tool plays a major role in the economics of cutting. Some of the adverse effects produced by a worn cutting tool are; 1) Poor dimensional control, 2) Unacceptable surface quality, 3) Increased power consumption, 4) Increased tool regrinding cost, 5) Increased machine down time, etc. From the above it is seen clearly that as the tool starts wearing out, the cost of machining goes up. The advantage of using more wear resistant tools are; a) They have a longer tool life

between regrinds or, b) For the same life, they permit the use of a severe cutting condition like higher speed ,feed and depth, thereby giving a higher rate of production for the same duration.

Cutting tool wear

Usually tool wear can be defined as the loss of metal by a cutting tool[1] and the several types of loss may be classified as follows.

1) The gradual loss of metal in the form of small wear particles of microscopic size.

2) A plowing action of hard particles in the metal cut.

3) A chipping action in which macroscopic or large pieces come off from the tool, and

4) Corrosion of the tool due to the use of overactive additives in the cutting fluids. This is most common in the case of carbide tools where cobalt binder is etched away by sulphur or chlorine containing oils.

The first of these types of wear is the most important and perhaps the least understood. When cutting steel, the tool is using a shear process and the metal is flowing plastically over the cutting tool.[2] Cast iron machining seems to be a fracturing of the metal ahead of the cutting tool.

Figure 1 shows an orthogonal view of a cutting tool, chip and work material being cut. The two places of wear are on the face of the tool and on the clearance angle which classifies the wear into the crater wear and the flank land

[1]These numbers refer to Bibliography

wear.

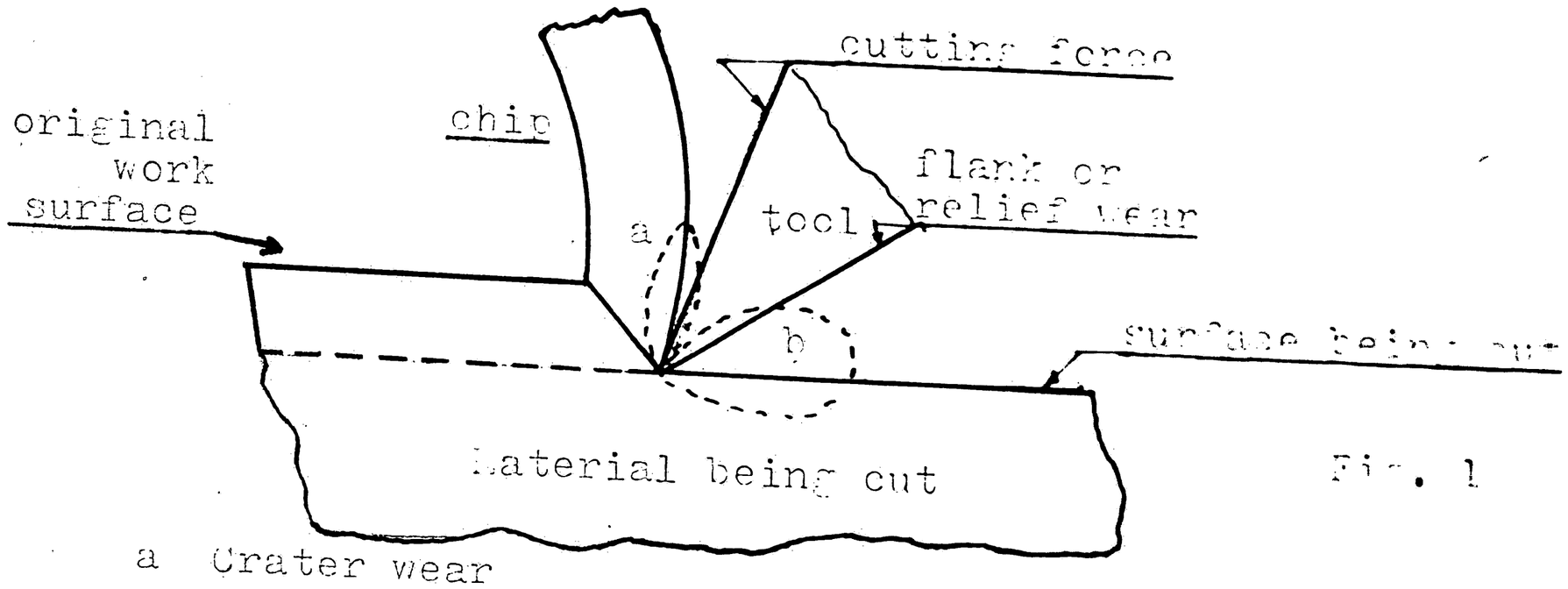


Fig. 1

a Crater wear

b Flank wear

The resulting wear of a cutting tool takes place in the presence of extreme temperature and stresses. The wear of a cutting tool is the result of one or a combination of the following.[3]

1) metal transfer
2) plowing
3) solid state diffusion.

Microscopic examination of the interface between the tool and the chip would reveal minute asperities. The cutting force causes plastic deformation between two asperities. This plastic deformation results in rather severe work hardening such that the hardness of the material at this interface is much higher than the parent materials. The velocity of the chip with respect to the tool causes these minute plastic welds to break in an area behind the strain hardened

areas. This form of wear is defined as metal transfer. This metal transfer may be in either direction. That is, from the work material to the tool as well as from the tool material to the chip. The former is known as the built-up edge and the latter is known as the crater wear. This form of wear may also take place on the flank area of the tool when it is rubbed by the newly generated work surface.

Plowing wear is caused by the work-hardened particles sliding across either the face or the flank of the tool.

Solid state diffusion is the exchange of atoms from one atomic lattice to the other. Solid state diffusion in part can account for wear in both the flank area as well as the crater area.

Trent[4] has suggested a theory of the crater wear postulated on diffusion and alloy formation at the tool chip interface. By the nature of action of the heated chips sliding on the top surface of the tool it appears logical to regard the resultant wear as frictional type.[5] This wear can be attributed to two mechanisms.

a) Adhesion and asperity-transfer wear in which rupture occurs in a thin layer of tool material adjacent to the tool chip interface as a result of weakening due to the diffusion and alloy formation. For a given tool-work pair, temperature and its distribution at the sliding contact are the governing factors.

b) Abrasion or plowing wear which depends primarily upon

the relative hardness of the tool and the chip under cutting conditions, the amount and distribution of hard constituents, (including the impurities) in the work material, the degree of strain hardening, etc.

Holm[6] has proposed a theory of transfer wear based on the fundamental concept that plastic deformation of the asperities form the true area of contact between the rubbing surfaces. During sliding, for every encounter of a surface atom in the real area of contact with an atom of the mating surface, there was a statistically constant probability of either of the two atoms being torn from its parent surface. With these hypotheses it can be shown[5] that the worn volume per unit sliding distance, W/S is

$$\frac{W}{S} = Z \cdot \frac{P}{H}.$$

Where Z = Probability of metal removal, number of atoms worn away per atomic encounter.

P = Normal load.

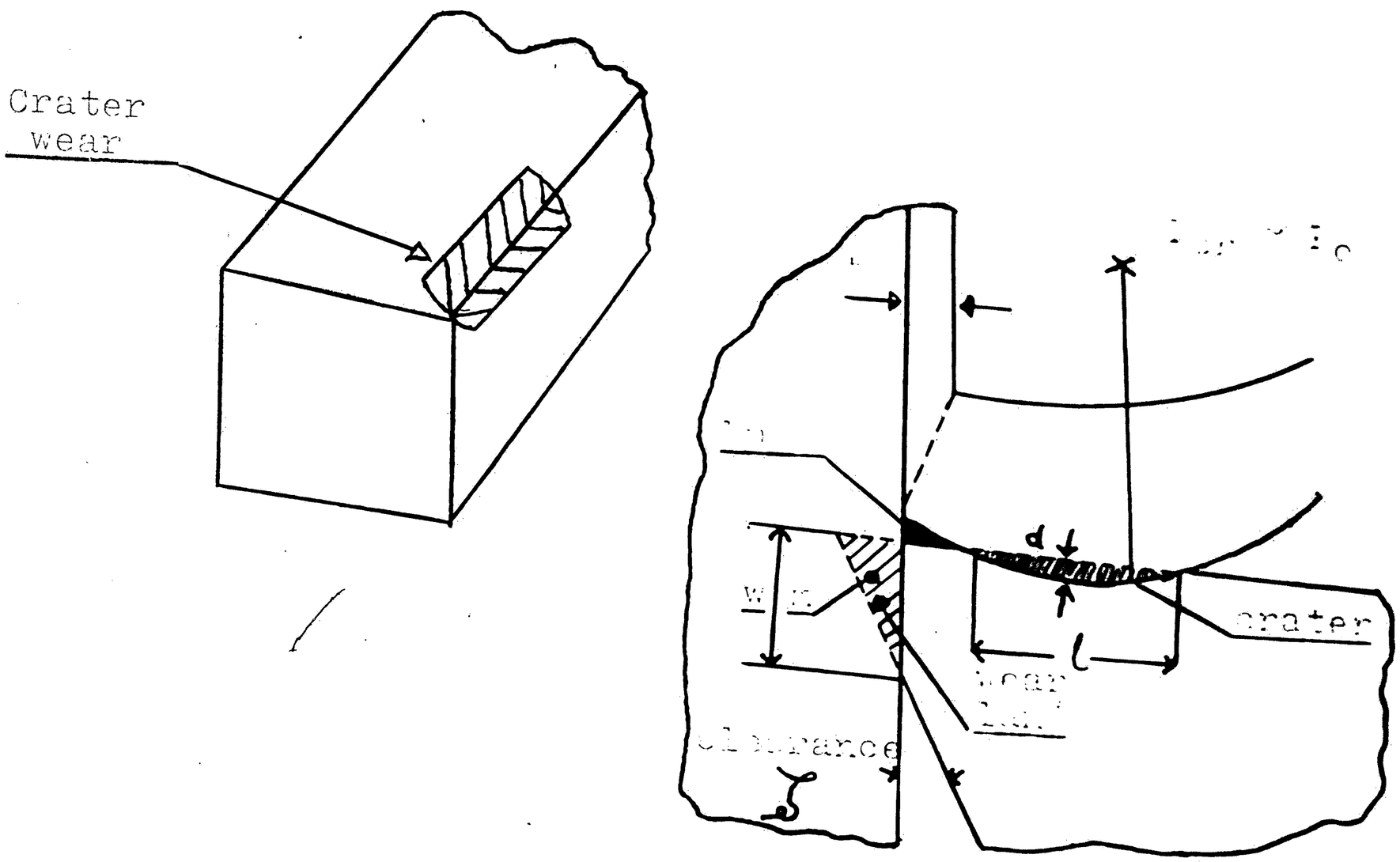
H = Mean pressure hardness of the softer material at the point of contact.

Burwell and Strang[7] questioned and changed the concept of atomic encounter postulated by Holm and replaced it by the asperity encounter. Following an analysis of the experimental results they concluded that the adhesion wear could be expressed in a form essentially like that of Holm,

$$\frac{W}{S} = K.\ F/H..$$

Where K is the fraction of real area of contact which results in a wear product. From these it can be readily seen that the prime factor is the local temperature at the actual contact area.

Tool wear Geometry



The figure above shows the cross section views of a single point cutting tool after considerable use. The wear occurs on two zones as shown in the sketch. These two wears are; 1) the flank land wear or simply the flank wear, and 2) the crater wear.

Flank wear

The flank land wear occurs on the front clearance or

the flank of the tool. This wear is generally characterized by the length of the wear-land w. Since the clearance or relief angle is very small (say 5 to 10°) we can approximate the flank wear volume.

$$V_f = \frac{w^2 l \tan}{2} \qquad (7a)$$

. Crater wear

The crater wear occurs on the top rake face of the cutting tool having a shape more or less circular in nature with a mean radius of curvature ρ_{cr}. The crater wear does not extend up to the tip of the tool and may be at a distance m from the tip of the tool. The size of the built up edge (B.u.e.) is usually commensurate with m. The average length and maximum depth d can be easily measured from which the volume of the crater wear can be found from the equation

$$V_{cr} = \frac{2}{3} \text{ b.d.l.} \qquad (7a)$$

The crater radius of curvature ρ_{cr} is found essentially equal to the initial radius of chip curvature ρ_o. The crater wear can be measured in fact by many ways. The wear length on the two x,y coordinates can be measured or the maximum depth of the wear from the Rake face could be used or the total volume of the metal removed from the tool (wear) could be measured by radioactive methods or by measuring the crater wear area by projecting it on an optical comparator.

The crater wear in a tool takes place in the following

manner. Initially a small built up edge is formed of a size and shape that conforms with the initial chip curvature ρ_o. As the crater is developed (also conforming to ρ_o), the built up edge becomes smaller. When the crater and the flank wearland join, the built up edge disappears. Under the high speed cutting conditions the crater wear is so rapid that the flat rake face represents only a transient portion of the tool life (10 to 20%). The built up edge is also transient. The most evident outward effect of tool wear is the manner in which the chip changes the shape. The chip becomes smaller in size and more tightly curled as against a straight ribbonlike chip.

Object and Scope of the Investigation

The primary object of this investigation is to determine the effect of cryogenic treatment on the performance of a high speed steel single point tool.

Experience has shown that the tool that wears the least ranks the best in a group of tools for the same cutting conditions and for a given length of time. Seven different kinds of heat treatments are employed and the cutting performance of each kind of tool is compared with the other. On the whole, twelve different cutting conditions are used and the crater wear areas of the tools, machining for three for each cutting condition, are noted for three different time values. Originally, the experiment was started with estimating the length of the flank land wear. When the tool failed mainly due to crater wear rather than flank land wear the idea of measuring the flank land wear was given up and instead, the measurement of the crater wear was taken. The cutting conditions employed are mainly rough turning conditions. So the measurement of surface finish is not taken into account. Also since the noted variations in the dimensions of the work piece are less than 0.010" from the start to the end of the cut for a specific condition of cutting and for the given time, this is also not taken into account.

The crater wear area for each kind of tool for various cutting conditions are noted and these are used to compare the performance characteristics of the seven different kinds

of tools.

Purpose and Theory of Heat Treatment

Theory:- Many steels, when quenched from the austenite region, do not transform completely to martensite even at the surface. At room temperatures such steels consist of martensite and retained austenite. In addition to it, undissolved carbides may or may not be present. It is the carbide that gives the wear resistance properties to a cutting tool. The retained austenite is unstable and may slowly transform while the steel is in service. Since this transformation is accomplished by an increase in volume of about 4 to 5%, residual stresses are set up in addition to that already present, or actual dimensional changes occur. For these reasons even a small percentage of retained austenite is undesirable especially in some applications like gage blocks, and closely fitting machine parts. The amount of retained austenite in a specimen increases if a higher austenizing temperature is employed. The time of austenization also has an effect on the amount of retained austenite in the specimen. The longer the austenizing period, the greater will be the amount of retained austenite. Since a particular minimum temperature is required for austenizing and also a certain minimum time is required for the homogenization for an alloy steel at the austenizing temperature, these two factors cannot be kept below a specific

minimum value to reduce the amount of retained austenite in the specimen. The solution is that if we lower the quenching temperature, then the amount of retained austenite in the specimen will be a minimum. A cryogenic quenching of the tool specimens can be done to transform more of retained austenite to martensite thereby reducing the quantity of the retained austenite in the specimen. Cryogenics is the science dealing with low temperatures (sub critical temperatures).

On cooling the high speed steel tool bits cryogenically to a sub zero temperature, some of the retained austenite present in the steel transforms to martensite, which is the hardest constituent of the metal in the phase diagram. So as the martensite increases, the tool is going to be harder which results in better wear resistance properties and a longer tool life. With these facts in mind, it is decided to carry out this investigation.

The basis for heat treatment of all the steels lies in the fact that when the steel is heated to a particular temperature, a structural change results. Tool steels are given a high temperature austenetizing treating procedure to produce a structure of austenite and carbide. On quenching the steel, it gives martensite carbide together with some retained austenite.[9]

The mixture of ferrite and carbide that exist in the steel at low temperature will transform to austenite. Austenite can dissolve much larger volumes of carbide than

the ferrite and on cooling from the austenizing temperature, the size and the distribution of the ferrite particles or aggregates can be controlled by controlling the cooling procedure. It is through this control and distribution we are able to obtain the widest mechanical properties obtainable in any engineering steel.

On cooling the steel from the austenitic temperature, austenite starts decomposing into martensite. It is this martensite that is the principal constituent of a hardened steel. Martensite has a body-centered tetragonal lattice in contrast to the body-centered cubic lattice of ferrite and has shown the same composition of the parent austenite.

The formation of martensite from the austenite takes place on cooling the austenite. A certain amount of new martensite appears at each temperature through [illegible] present. If the cooling is stopped after a certain amount of martensite has formed, transformation to martensite will stop for all practical purposes. Further cooling is necessary to initiate the transformation once more. The temperature at which the austenite starts decomposing into martensite is called the Ms (martensite start) temperature. On further cooling below the Ms temperature, martensite transformation continues through room temperature to sub zero temperatures and eventually stops short of consuming all the remaining austenite at a second temperature called the Mf (martensite finish) temperature.[1] [illegible]

[illegible] is a function of [illegible] austenite (inherited from the austenite) [illegible] of the relatively soft austenite remains [illegible] of cooling.

This retained austenite is [illegible] to fresh martenite during the tempering operations or [illegible] during aging at room temperature causing [illegible] sional changes, brittleness and [illegible]. A large percentage of retained austenite may prevent the attainment of the desired hardness because the austenite transforms to a product softer than martensite during the tempering operations. The amount of retained austenite depends largely on the following.

a) Ms temperature

b) Quenching bath temperature

c) Time for which held at an austenizing temperature.

The higher the Ms temperature, the lower will be the amount of retained austenite for a given quench bath temperature. Increases in carbon content lower the Ms temperature. Higher austenizing temperatures lower the Ms temperature by dissolving more of the excess carbides in the austenite prior to quenching. Mf, the martensite finish temperature, on the other hand appears to be fairly constant at - 250° F. (-155° C) for carbon and alloy steels and -150° F (-100° C) for the high speed steels[12] regardless of the position of the martensite start Ms, temperature. Mf

temperature can be considered as the starting point of martensite transformation from austenite for all practical purposes.

Tempering operations

The quenching of the steel from the austenetic region results in the formation of the martensitic structure. The tempering process in the case of an alloy steel causes this to decompose, with the precipitation of one or more carbides in a matrix of ferrite. This results in the loss of strength and hardness with a compensating gain in toughness and ductibility. In some cases of tool steels, as the tempering operation proceeds, the hardness begins to increase, or at any rate decreases less rapidly.[13] This phenomenon is called secondary hardening and generally implies that a new type of precipitation has set in. If on the other hand, the original quenching results in the retention of an austenetic structure, the tempering process may cause simple precipitation hardening, and in this case the tempered alloy is much stronger and harder than the quenched material.

The hardened high speed steel contains highly alloyed martensite around 58 to 80%, highly alloyed retained austenite around 15 to 30% and undissolved carbides around 5 to 12%.[10] The steel in this condition is hard, highly stressed, brittle and dimensionally unstable. The tempering operation renders the steel useful by alleviating the internal stresses and brittleness without impairing the hardness.

This is achieved by heating the steel around [illegible] one or more times. The steel develops secondary hardness which is of the same order of magnitude of the original hardness.

The tempering of high speed steel can be divided into four overlapping stages out of which only the first three are encountered in commercial practice. Investigations by Kuo,[18] Michel Papier[19] and Koh and Kohen[20] indicate that the following are the probable sequences during the tempering of high speed steel.[21]

Stage I

Softening is encountered with a drop of 2 to 4 points on the Rockwell C Scale hardness. From room temperature to 570° F., tetragonal martensite decomposes into cubic martensite with rejection of carbon as ε (epsilon) carbide which subsequently disappears with the precipitation of fine cemented carbide at 570° to 750° F. These phenomena occur on tempering up to about 750° F. The drop in hardness is accompanied by a drop up to 0.2 in specific volume and an increase in magnetism. Nothing happens to the bulk of retained austenite at this stage.

Stage II

The second stage of the tempering operation can be said to be between 750° to 1050° F., involving the re-solution of a portion of cementite and precipitation from tetragonal martensite of an alloy carbide accompanied by a pronounced

precipitation hardening.

Stage III

This involves the transformation of residual austenite on cooling from the tempering temperature, probably produced by a precipitation of an alloy carbide from the austenite. This is accompanied by a large increase in the specific volume at room temperature, a continued rise in room temperature hardness, and a sharp increase in hot hardness. This stage overlaps the second stage at the end of the second stage phenomenon.

Stage IV

This stage is seldom encountered in the commercial practice of tempering and is associated with a drastic softening of the high speed steel on tempering above a temperature of about 1200° F.

Refrigeration

The effect of refrigeration has to do solely with the decomposition of the retained austenite to martensite. As the specimen is cooled more and more, the remaining austenite is progressively transformed to martensite. The amount of transformation is a function of the minimum temperature reached.

When a quench-hardened piece consisting of martensite and retained austenite is refrigerated, it [illegible] ly in hardness, due to the remaining austenite which is soft being transformed to a relatively hard martensite. A piece

which is in the hardness range of 60 to 65 Rockwell C, may become from ½ to 2 points harder[14] on the Rockwell C scale. The hardness after refrigeration may usually be looked upon as the hardness of the completely martensitic condition of steel in as much as the piece was, before refrigeration, completely martensitic because of the presence of small regions of retained austenite; these regions have now been made martensitic. So by inference, then, the apparent hardness of the quenched steel martensite was slightly impaired by the presence of the retained austenite which is comparatively soft. Since refrigeration decomposes more of the austenite into martensite, it is logical to think that the hardness of the piece increases to what it was before the refrigeration treatment.

Tool Specimen and Heat Treatment

Tool specimen

The tool specimen is in the form of rod in square section 1/2" square section and 3/16" thick. The material is a grade of high speed steel.

Composition of M 15 Grade of High Speed Steel

Carbon	-	1.5%
Tungsten	-	12%
Chromium	-	4%
Cobalt	-	5%
Vanadium	-	5%
Molybdenum	-	nil

Heat treatment

Several different combinations of heat treatments are given to the tool material in order to deliberately vary the percentage of retained austenite in the tool material. Two different electric furnaces, one for the preheating of the tool material around 1000° F. and the other for austenizing the tool material around 2270° F. are employed.

To protect the tool material from decarburization and scaling at elevated temperatures, the specimens are completely painted on all the sides with a surface protection coating and allowed to dry for one hour. Special austenetic heat treating stainless steel bags are used to keep the tools in a completely air tight atmosphere thereby preventing the possibility of scaling or decarburization of the specimen at the

elevated austenizing temperature.

First, a preheating of the specimens at a temperature of 1000° F. is employed to minimize the soaking time at the austenizing temperature to prevent the excessive grain growth. Fifteen minutes preheating time is employed in all the cases. An austenizing temperature of 2270° F. and a soaking time of 5 minutes at the austenizing temperature are employed. After austenizing the tool specimens for 5 minutes, the tool specimens are air-hardened by vigorously agitating them in the still air after puncturing the stainless steel bars. A tempering temperature of 1000° F. is employed for a time period of 1 1/2 hours. Various cryogenic quenchings are employed at -320° F. in liquid nitrogen. In all the cases the cryogenic quenchings are done only after the tool attains room temperature. Special austenetic stainless steel cryogenic tanks are used to store liquid nitrogen at -320° F. in which the tool specimens are quenched.

The following are the various combinations of heat treatments that are actually employed.

Treatment A

a) Preheat at 1000° F. for 15 minutes.

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Double temper at 1000° F. for 1 1/2 hours.

Treatment B

a) Preheat at 1000° F. for 15 minutes.

b) Austenize at 2270° F. for 5 minutes

c) Air harden by agitating in still air (to room temperature).

d) Temper at 1000° F. for 1 1/2 hours.

e) Cryogenic quench for one cooling cycle at -320° F. in liquid nitrogen.

f) Second temper at 1000° F. for 1 1/2 hours.

Treatment C

a) Preheat at 1000° F. for 15 minutes.

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Temper at 1000° F. for 1 1/2 hours.

e) Cryogenic quench for two cooling cycles at -320° F. in liquid nitrogen.

f) Second temper at 1000° F. for 1 1/2 hours.

Treatment D

a) Preheat at 1000° F. for 15 minutes

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Temper at 1000° F. for 1 1/2 hours.

e) Cryogenic quench for one cooling cycle at -320° F. in liquid nitrogen.

Treatment E

a) Preheat at 1000° F. for 15 minutes

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Temper at 1000° F. for 1 1/2 hours.

e) Cryogenic quench for two cooling cycles at -320° F. in

liquid nitrogen.

Treatment F

a) Preheat at 1000° F. for 15 minutes.

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Cryogenic quench for one cooling cycle at -320° F. in liquid nitrogen.

e) Temper at 1000° F. for 1 1/2 hours.

Treatment G

a) Preheat at 1000° F. for 15 minutes.

b) Austenize at 2270° F. for 5 minutes.

c) Air harden by agitating in still air (to room temperature).

d) Cryogenic quench for two cooling cycles at -320° F. in liquid nitrogen.

e) Temper at 1000° F. for 1 1/2 hours.

In the cases of treatments A, B and C, two tempering operations are done whereas in the other cases of D, E, F and G, only one tempering operation is done in each case. The second tempering operations are deliberately omitted for the cases D, E, F and G. This enables us to compare in these conditions whether the two tempering operations are necessary or whether one of them could be substituted by a cryogenic quench cooling.

The hardness values of the tools

After heat treating the tools, the specimens were ground perfectly on both sides. This is done for two reasons:

Firstly to provide a flat surface for the [illegible] hardness and secondly to remove the [illegible] burized surfaces. In all cases of specimens, the hardness is taken at 10 different places on both the sides of the specimen on the Rockwell C scale and the average value is taken in each case.

Tool Designation	Hardness Rc
A [illegible]	62.4 63.0 63.[illegible] 62.6 63.[illegible] 62.0 62.2

Estimation of Carbide Content

Theory: All the grades of high speed steels invariably contain four or more alloying elements. The effect of various alloying elements on the eutectoid carbon content is interesting. All alloying elements move the eutectoid to a lower percentage of carbon and thereby increase the amount of undissolved carbide,[22] otherwise known as excess carbide, in the hardened steel. Nickel has the minimum effect of forming excess carbides. Chromium and manganese form excess carbides in the intermediate range and titanium, vanadium, tungsten and molybdenum afford the greatest increase in excess carbide.

These excess alloy carbides in the composition of the tool steels lead to the improvements in the wear resistance

properties of the high speed steel tools. It is not only the amount of excess carbide that is present in the hardened steel decide the wear resistance property of the cutting tool, but the nature of that excess carbide. The larger the excess carbide, the greater is the wear resistance of the tool. Generally cutting tools with the highest wear resistance are those that have the greatest amount of the hard carbide in the structure.

Certain carbides like .02% and .2% are usually found only in the hardened and tempered steels. These carbides do not exist in the equilibrium state. Because these carbides have certain solubility for virtually all metallic alloying elements, they are generally designated as M_3C, M_7C_3 and $M_{23}C_6$ where M stands for all metal atoms. The commonly reported types in tool steel may include one or more of the following six general types.[23]

M_3C is essentially an iron rich carbide with orthorhombic structure of cementite. The M_3C occurs in the annealed steels at very low chromium, [illegible], manganese content, or with moderately low chromium.

M_7C_3 is a carbide rich in chromium which has a hexagonal structure Cr_7C_3. It is generally confined to medium and high chromium steels with moderate addition of alloying elements. In these types of steels, the carbides dissolve only partially when heated for hardening, leaving excess hard particles in the structure for a highly abrasion resistant steel. M_7C_3 has

been found in high tungsten and molybdenum, chromium steels after tempering or annealed for a long time.

M23C6 is also a chromium carbide but with face centered cubic structure of Cr23C6. When sufficient amounts of tungsten and molybdenum are present in this carbide, the chromium can be entirely replaced by iron to yield carbides. In most of the annealed steels this carbide is present. Manganese tends to concentrate in this carbide.

M6C is a face centered cubic lattic carbide which is tungsten and molybdenum rich. All the high speed steels contain these carbides. It was thought for a long while to be the only carbide in these steels and it is frequently referred to as "high speed steel carbide". On hardening, this M6C carbide leaves excess hard carbide particles in the resulting structure accounting for a good abrasion resistance to the steel.

M2C is a carbide having hexagonal structure and is a tungsten or molybdenum rich carbide. Usually this is not noted in the annealed steels. These occur only in the medium to high tungsten and molybdenum steels after quenching and tempering near the secondary hardness zone. M2C is responsible for the secondary hardness of the steel. Further tempering causes the disappearance of the M2C carbide and favors M6C or both the carbides.

MC is a vanadium rich carbide with face centered cubic

type structure. Titanium, columbium, tantalum and zirconium also form this carbide. Because of the strong carbide-forming tendency of these elements, a consistently appears in steels of moderate to high vanadium content, regardless of the other alloying additions. VC is a very strong hard carbide, extremely hard and resists dissolving to a marked degree. Consequently, most of the VC remains as excess particles in the hardened structure to impart exceptional abrasion resistance to the steel. The small amount of VC that is dissolved reprecipitates on tempering as very fine particles and appears to be responsible for the secondary hardening in vanadium steels.

From the above it is logical to conclude that - the higher the amount of excess carbide present in the steel after the hardening and tempering treatments, the greater will be the wear resistance of the tool. Also the tools with the highest wear resistance are those that have the greatest amount of VC carbide in the structure.

Estimation of carbide content (quantitative metallography)

Specimen preperation: After carrying out the several different kinds of heat treatments, the tool specimens are prepared for the quantitative metallography. After the heat treatment, a wet grinding operation of the specimen is done on an emery belt to remove the surface which may be decarburized or otherwise non representative of the bulk of the specimen followed by standard metallographic polishing using

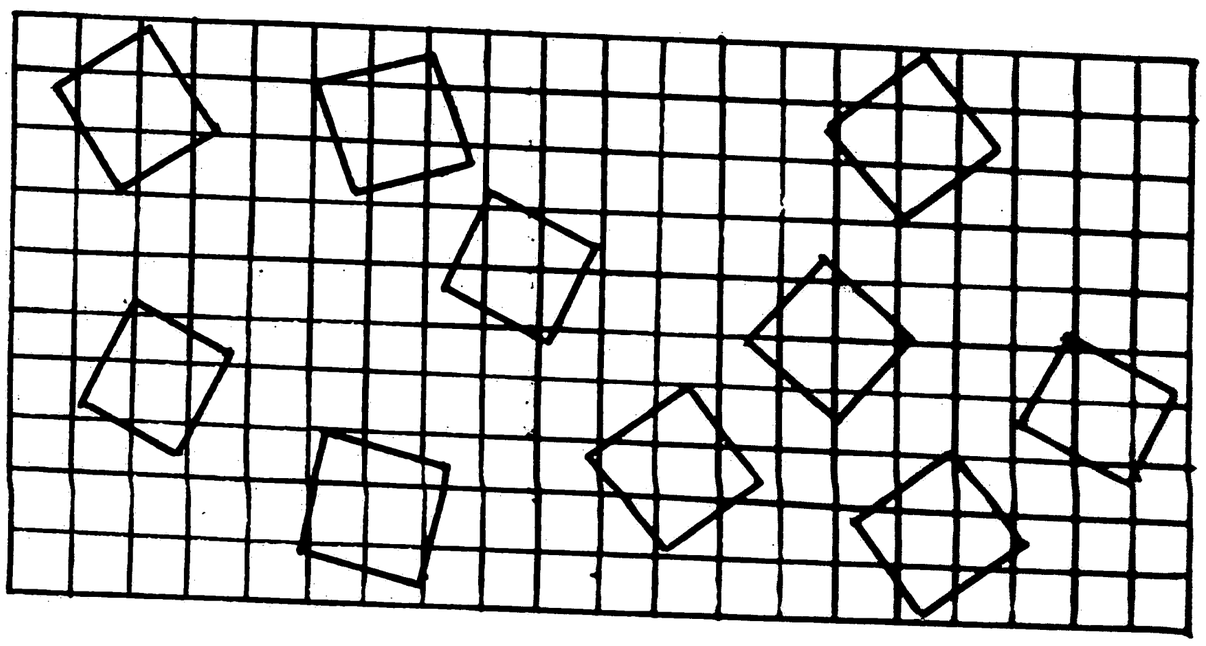
four different grits of surface finishing emery sheets using water as the coolant medium. Special care is taken not to produce excessive heat or plastic deformation of the tool during grinding and polishing operations which may introduce certain amounts of martensite as well as austenite. Then the surface is electrolytically polished and then etched in a solution of nital. A careful preparation of the specimen is absolutely necessary for the quantitative metallographic measurements, particularly the structures are not over etched, since a slight enlargement of small particles may nearly double their actual areas. Then the micro structure photographs of the seven different specimens are taken at 600 times magnification scale.

Measurement of volume fraction

Volume fraction of some or all the constituents in an alloy is very important in the field of quantitative metallography. Though both volume fractions as well as weight fractions are useful quantities, volume fraction is preferred generally because volume fraction can be determined unequivocally from the given sample alone, whereas additional information must be obtained in order to calculate the weight fractions.

Quantitative measurements of the volume fraction of a phase in an alloy can be obtained from the random two dimensional plane of polish in several ways. One way involves the measurements of areas; another, measurement of lineal

intercepts; and a third consisting of points. These are called areal analysis, lineal analysis and point counting, respectively.



Simple illustration of the equalities of areal, lineal, and point ratios. Random squares represent a phase, P, and the grid the total area, T, of the alloy.

Random squares represent a phase P, and the grid the total area, T, of alloy (from Quantitative Metallography by E. Underwood, A.S.M., Metals Engineering Quarterly, Aug.-Nov., 1961. Vol. no. 34).

$$f_V = \frac{V_P}{V_T} = \frac{L_P}{L_T} = \frac{A_P}{A_T} = \frac{P_P}{P_T}$$

From the above figure, the area ratios $\frac{A_P}{A_T}$ of the randomly arranged squares, A_P and the total area Ar is seen to be 20%, and the ratio of grid intersection $\frac{P_P}{P_T}$ is also close to 20%.

Because each of the methods shown above give almost the same order of accuracy in the result, any of the methods can

be used in determining the volume fraction of carbide. A lineal count method was employed to determine the volume carbide fraction in the tool specimen. Since the alloy did not possess any directional characteristics, only one plane of polished surface is used for estimation purposes. For the degree of precision desired, the requisite number of measurements can be readily determined. As a thumb rule, however, about ten measurements at random give adequate coverage for all practical purposes.[25]

Lineal analysis

The method of obtaining the volume fraction by lineal analysis is based on the line ratios. This method is developed by Rosiwal.[26]

For one phase, the equation simply is

$$f_V = \frac{L_P}{L_T} = \frac{V_P}{V_T}$$

Where L stands for the length, V for volumes, f_V the volume fraction and the subscript refers to the phase, P, and the total part, T, of the alloy selected for the measurement. The above equation shows that the length ratio equals the volume ratio which of course equals the volume fraction of phase P in an alloy. Random straight lines are drawn across the structure to intersect both the matrix and precipitate. By adding up the fractional lengths of the lines that fall over the precipitate and dividing the total length of random line over the micro structure, f_V is obtained from the ratio $\frac{L_P}{L_T} = f_V$.

If more than one phase is present say like α, β and γ, then the lengths of line intersects by each phase must be taken seperately, and the volume fraction is given by

$$f_\alpha = \frac{L_\alpha}{L_T} \; ; \; f_\beta = \frac{L_\beta}{L_T} \text{ and } f_\gamma = \frac{L_\gamma}{L_T}$$

In the actual estimation, the value of f_v by the lineal ratio is accomplished as follows.

Straight lines drawn to scale on a transparency are superimposed over the photo micrograph and at random places, the fractional lengths that fall over the carbide and the total length are noted. These fractional lengths for a given total length are summed up and then the sum of the fractional lengths is divided by the total length to get the volume fraction f_v.

Calculation of carbide (sample calculation for tool 1).

The total length used for the measurement of carbide fraction by volume is L_T = 30 units.

number of random observations - 10.

Total overall length - 30x10 = 300 units.

Total sum of fractional lengths for Tool A = L_F = 88.

Percentage volume fraction of carbide $V_f = \frac{88}{300} \times 100 = \underline{29.3}$

Tool B

Total overall length L_T = 30x10 = 300 units.

Sum of fractional lengths L_P = 101 units.

Volume fraction percentage $V_f = \frac{101}{300} \times 100 = 33.$

Tool C

Total overall length L_T = 30x10 = 300 units.

Sum of the fractional lengths L_P = 111 units.

Volume fraction percentage $V_f = \frac{111}{300} \times 100 = 37$.

Tool D

Total overall length L_T = 30x10 = 300 units.

Sum of the fractional lengths L_P = 94 units.

Volume fraction of carbide $V_f = \frac{94}{300} \times 100 = 31.3$.

Tool E

Total overall length L_T = 30x10 = 300 units.

Sum of the fractional lengths L_P = 99 units.

Volume fraction of carbides $V_f = \frac{99}{300} \times 30 = 33$.

Tool F

Total overall length L_T = 30x10 = 300 units.

Sum of the fractional lengths L_P = 73 units.

Volume fraction of carbides $V_f = \frac{73}{300} \times 100 = 24.3$.

Tool G

Total overall length L_T = 30x10 = 300 units.

Sum of the fractional lengths L_P = 78 units.

Volume fraction of carbides = $\frac{78}{300} \times 100 = 26$.

Tool Designation	Volume Percentage of Carbi...
A	29.3
B	33.6
C	37
D	31.3
E	33
F	24.3
G	26

Estimation of the amount of retained austenite in the tool specimen by X-ray diffraction method

Chemical analysis by diffraction

Introduction. A given substance always produces a characteristic diffraction pattern, whether the substance is present in the pure state or as one constituent of a mixture of substances. The diffraction method of chemical analysis is based on this fact. Both qualitative as well as quantitative analysis are possible by means of diffraction analysis. The qualitative analysis for a particular substance is accomplished by the identification of the pattern of that substance whereas quantitative analysis is accomplished by the intensities of the diffraction lines due to one constituent of a mixture depending upon the proportion of that constituent in the specimen.

The particular advantage of the diffraction analysis is that it discloses the presence of a substance as that substance actually exists in the sample, and not in terms of the constituent chemical elements. For example, if the plain carbon steel is analyzed chemically, the analysis reveals

only the amounts of iron, carbon, manganese etc., which the steel contains, giving no information regarding the phases present. It won't be possible by chemical analysis to say whether the steel in question is wholly martensitic or whether it contains both martensite and austenite or whether it is composed of ferrite and cementite. Diffraction analysis method gives an answer to these questions.

Diffraction analysis is therefore very useful whenever it is necessary to know the state of a chemical combination of the elements involved or the particular phases in which they are present. In addition to that, comparing to ordinary chemical analysis, the diffraction analysis has the additional advantage that it is much faster, requires only a very small sample and is non destructive.

Quantitative analysis

Direct comparison method: This method is of the greatest metallurgical interest because it can be applied to massive, polycrystalline specimens. This is a very popular method and simple method which is widely used in estimating the amount of retained austenite in a given specimen.

Quantitative microscopic examinations are fairly satisfactory as long as the austenetic content in the specimens is fairly high but becomes undesirable below about 15 to 20% of retained austenite in many steels. The X-ray method on the other hand gives quite accurate results and so is of a great practical importance.

Theory

Assuming that the hardened steel contains only two phases, say martensite and austenite, [illegible] determine the composition of the mixture when the two phases have the same composition but different crystalline structures. (Martensite is body centered tetragonal and austenite is face centered cubic).

Quantitative analysis is based on the fact that the intensity of diffraction pattern of a particular phase in a mixture of phases, depends on the concentration of that phase in that mixture. The relation between intensity and concentration is not generally linear since the diffracted intensity depends markedly on the absorption coefficient of the mixture and this itself varies with the concentration.

The exact expression for the intensity diffracted by a single phase powder [illegible] in a diffractometer is

$$I = \left(\frac{I_o e^4}{m^2 c^4}\right)\left(\frac{\lambda^3 A}{32\pi r}\right)\left(\frac{1}{v^2}\right)\left[|F|^2 P\left(\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}\right)\right]\left(\frac{e^{-2M}}{2\mu}\right)$$

where

I = Integrated intensity per unit length of the diffraction line.

Io = Intensity of the incident beam.

e = charge of the electron.

m = mass of the electron

c = velocity of light.

r = radius of diffractometer circle.

λ = wave length of the incident beam of light.

A = Area of the cross section of the incident beam.

v = volume of unit cell.

P = multiplicity.

θ = Bragg angle.

e^{-2M} = the temperature factor which is a function of θ, the Bragg angle.

μ = linear absorption coefficient.

In the above equation, putting

$$k^2 = \left[\frac{Ioe^4}{m^2c^4}\right]\left[\frac{\lambda^3 A}{32\pi r}\right] \quad \text{and}$$

$$R = \frac{1}{v^2}\left[|F|^2 P \left(\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}\right)\right]\left(e^{-2M}\right)$$

We have I, the diffracted intensity given by the expression

$$I = \frac{k_2 R}{2\mu}$$

where k_2 is a constant, independent of the kind and amount of the diffraction substance and R depends on the values of θ, k, h, l and also the kind of substance.

Designating the austenite by γ, and the martensite by α, we can write the above equation as

$$I_\gamma = \frac{k_2 R_\gamma C_\gamma}{2\mu m} \qquad \text{(a)}$$

and

$$I\alpha = \frac{k_2 R_\alpha C_\alpha}{2\mu m} \qquad \text{(b)}$$

Dividing (a) by (b), we have

$$\frac{I_\gamma}{I_\alpha} = \frac{R_\gamma C_\gamma}{R_\alpha C_\alpha}$$

The values of $\frac{C_\gamma}{C_\alpha}$ can therefore be obtained from a measurement of $\frac{I_\gamma}{I_\alpha}$ and a calculation of R_γ and R_α. Once the value of $\frac{C_\gamma}{C_\alpha}$ is known, then the value of C_γ can be found from the additional relationship $C_\gamma + C_\alpha = 1$.[16]

We can thus make an absolute measurement of the austenite content of the steel by direct comparison of integrated intensity of a martensite line.

Extending the same argument, if this contains a third phase of iron carbide also, we have the equation

$$C_\gamma + C_\alpha + C_c = 1$$

Microphotometer traces of Debye-Scherrer patterns of hardened 1.07 percent carbon steel. (E.L. Averbach and M. Cohen, Trans. AIME 176, 401, 1948)

Suitable austenite lines are the 200, 220 and 311 lines. They may be compared with 002-200 and 112-211 martensite doublets. These doublets are not usually resolvable into seperate lines because all lines are usually quite broad, both from the martensite and austenite. It can be readily inferred from the figure shown on the preceding page that refrigeration done immediately after the quench can decrease the amount of retained [illegible] on an interception in the quench followed by air cooling can increase it. The causes of line broadening are the non uniform micro strains present in both the phases of the quenched steel and, in many cases, the very fine grain size.[17]

In calculating the value of R, for a particular diffracted line, various factors should be kept in mind. The unit cell volume v is calculated from the measured lattice parameters which are functions of carbon and alloy contents. When martensite contents are unresolved, the structure factor and multiplicity of the martensite are calculated on the basis of a body centered cubic cell. This procedure in effect adds together the integrated intensities of the two lines of doublets which is exactly what is done experimentally when the integrated intensity of unresolved doublet is measured.

Experiment and Equipment set up for the measurement of Retained Austenite

A wet grinding operation followed by a standard metallographic polishing is done on the specimen in order to

remove the surface layer which may be decarburized or otherwise non-representative of the bulk of the specimen. Care is taken not to produce excessive heat which may decompose a certain amount of both martensite as well as austenite. The surface is then electrolytically polished and then etched in a solution of nitol.

An X-ray spectrometer can be used as a tool in diffraction analysis. This instrument is known as diffractometer when it is used with the X-rays of known wave length to determine the unknown placings of crystal planes, and as a spectrometer in the reverse case, when crystal planes of known spacings are used to determine unknown wave lengths. The diffractometer is always used with monochromatic radiation and measurements are made on either single crystals or polycrystal specimens.

The specimen is then mounted on the X-ray diffractometer and a molybdenum target is used for the diffraction analysis. The sample is rotated between 31 to 39.5° and the intensity line peaks for carbides, martensite and austenite are plotted automatically.

The following are the actual test conditions used.

Analysis - For the measurement of retained austenite.

Material - T 15. I.S.S.

Target - Molybdenum.

K.V. - 40

MA - 18

Filter - Zirconium

Detector - 1-0 ...

Detector type - S-c

Voltage - 1260

Height - 60 mm

Width - 15 mm

Count rate - 2×10^4

Chart speed - 20 cm/min.

Attenuation - 10

In the chart, the areas of the austenite peaks between 32 and 33 and between 38 and 39 degrees are measured. The curves are approximated by rounding off and a planimeter is used for the actual measurement of the areas. All the areas are measured five times and then averaged out to get the mean areas. Care is taken to use the same planimeter in all cases and all the areas are measured on the same scale in order to minimize the possibility of errors. Similarly, the martensite peaks between 34 and 36 degrees are approximated by rounding off in the same way as done in the case of austenite peaks, and the mean value of area is calculated after measuring the area five times in each case.

The expression for the intensity diffracted by a single crystal plane specimen in a diffractometer is

$$I = \left(\frac{I_0 e^4}{m^2 c^4}\right)\left(\frac{\lambda^3 A}{32\pi r}\right)\left(\frac{1}{v^2}\right)\left[|F|^2 p \frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}\right]\left(\frac{e^{-2M}}{2}\right)$$

This expression can be written as

$$I = \frac{k_2 R}{2\mu}$$

where k_2 is a constant, independent of the kind an amount of the diffraction substance and [illegible] h, l and the kind of substance. Designating austenite by γ and martensite by α, we can write the equation as

$$I_\gamma = \frac{k_2 R_\gamma J_\gamma}{2\mu_m}$$

and

$$I_\alpha = \frac{k_2 R_\alpha J_\alpha}{2\mu_m}$$

Dividing one by the other, we have

$$\frac{I_\gamma}{I_\alpha} = \frac{R_\gamma J_\gamma}{R_\alpha J_\alpha}$$

Rewriting the equation

$$C_\gamma = \frac{I_\gamma R_\alpha J_\alpha}{I_\alpha R_\gamma}$$

Because martensite has the same composition of the parent material, the above equation simplifies to the form

$$C_\gamma = \frac{1.34\ I_\gamma}{I_\alpha + 1.4\ I_\gamma}$$

Calculation of retained Austenite

Using a planimeter, the areas of the austenite peaks between 32 and 33° are measured five times and the average area , in each case is found out. Similarly, the average areas γ_2 between 38 and 39.5° are found. The value I_γ is found by adding the average areas γ_1, and γ_2 in each case.

Similarly, the average areas of the martensite peaks between 34 and 36 is measured using the planimeter and measuring areas 5 times over the contour. This mean area

gives I_α, the value of the area of martensite peak.

In all the cases, all the areas are measured using the same planimeter and on the same scale to minimize the possibility of error.

Calculations

Tool A Average area of austenite γ_1 = 1.7 sq. in.

Average area of austenite γ_2 = 0.984 sq. in.

Total average area of austenite = $\gamma_1+\gamma_2$

= 2.684

Average area of martensite I_α = 13.10

The value of R_γ, retained austenite = $\frac{1.4I_\gamma}{I_\alpha+1.4I_\gamma}$

% value of $R_\gamma = \frac{1.4\ I_\gamma}{I_\alpha+1.4I_\gamma} \times 100$

$= \frac{1.4\ (2.684)}{15.734} \times 100 = \underline{23.81\%}$

Tool B Average value of γ_1 = 1.31 sq. in.

Average value of γ_2 = 0.88 sq. in.

Average value of α = 13.84 sq. in.

% value of $R_\gamma = \frac{1.4x2.19}{16.03} \times 100 = \underline{19.13\%}$

Tool C Average value of γ_1 = 0.946 sq. in.

Average value of γ_2 = 0.420 sq. in.

Average value of α = 12.69 sq. in.

% value of $R_\gamma = \frac{1.4x1.366}{14.056} \times 100 = \underline{13.6\%}$

Tool D Average value of γ_1 = 1.536 sq. in.

Average value of γ_2 = 0.96 Sq. in.

Average value of α = 12.92 sq. in.

% value of $R_\gamma = \frac{1.4 \times 2.536}{15.546} \times 100 = \underline{22.83\%}$

Tool E Average value of γ_1 = 1.400 sq. in.

Average value of γ_2 = 0.884 sq. in.

Average value of α = 13.4 sq. in.

% value of $R_\gamma = \frac{1.4 \times 2.284}{15.684} \times 100 = \underline{20.4\%}$

Tool F Average value of γ_1 = 2.1 sq. in.

Average value of γ_2 = 0.86 sq. in.

Average value of α = 12.52 sq. in.

% value of $R_\gamma = \frac{1.4 \times 2.92}{15.482} \times 100 = \underline{26.2\%}$

Tool G Average value of γ_1 = 2.4 sq. in.

Average value of γ_2 = 0.9 sq. in.

Average value of α = 14.0 sq. in.

% value of $R_\gamma = \frac{1.4 \times 3.3}{17.3} \times 100 = \underline{26.7\%}$

The actual value of percentage volume fraction of retained austenite taking into account the carbide volume fraction

The calculations shown above give the value of retained austenite percentage without taking into account the carbide content in the specimens. The actual value of % volume fraction of retained austenite taking into account the carbide

[illegible] is calculated as follows.

Sample calculation for col ..

The percentage volume fraction of carbi[illegible] = 29.3%

% vol. fraction of retained austenite without taking into account the carbide content = 23.91%

The actual value of volume fraction of retained austenite taking carbides into consideration

$$= \frac{23.91*(100-29.3)}{100}$$

= 16.91

The table shown gives the value of the volume fraction of retained austenite, carbides and the hardness for each different kind of tool. The hardness is taken at 10 places in each case and the average hardness is indicated in the table for each case. All the hardnesses are measured on Rockwell C scale.

Tool Designation	% volume of Carbide	% volume of Retained Austenite	Hardness Rc
Tool A	29.3%	16.91	62.4
Tool B	33.6%	12.63	63.0
Tool C	37%	8.55	63.8
Tool D	31.3%	15.7	62.6
Tool E	33%	13.67	63.2
Tool F	24.3%	20.36	62.0
Tool G	24.6%	19.75	62.2

The purpose and setup of the experiment

The primary object of this investigation is to study the effect of cryogenic treatment on the performance of high speed steel cutting tools.

Even though there are a number of ways of evaluating the

performance of a cutting tool, many of them have been found useful in the laboratory and are not equally useful in industry. One of the most important parameters is the wear of the cutting tool which plays a major role in the economy of metal machining. The experiment was started with an idea of estimating the flank wear on the tool while cutting SAE 1117 material. The cutting was done dry without using any coolant. First a finish cutting condition was employed, using a high speed, low feed and less depth, and the flank wears measured for various cutting conditions. The surface finish on the work material for each condition of cutting at specified intervals of times were also noted. This trial cut indicated that the tool failed mainly by a crater wear rather than a flank wear. Since the measurement of flank wear led to a blind path, the experiment was altered by changing the cutting condition to a roughing condition using a relatively low surface speed, a higher feed rate and a greater depth of cut. Instead of flank wear, crater wear measurement was therefore examined. Since the cutting conditions employed were roughing ones, the measurement of surface finish is dropped and instead, the change in the dimension of the work material for each cutting condition at the start and the end of the cut are noted for various time intervals. It is noted that in all the cases of cutting, the change in dimension of the work material from the start to the end of the cut is negligible (less than the allowable tolerance of roughing cuts).

so the dimensional change in the work piece material was also not taken into account.

Test practice

The work material used is SAE 1117 bar, cold rolled, having a diameter of 7".

The composition and the average mechanical properties of SAE 1117 material

Carbon	0.14-0.20%
Manganese	1.00-1.30
Phosphorous	0.040% (max.)
Sulphur	0.08-0.13%
Tensile strength	62,000psi
Yield strength	34,000psi
Brinell hardness	121 BHN (average)

All the work materials used throughout the experiment are of a single batch from the same manufacturer thus eliminating the possibility of the large variations in the properties among the bars.

Standardized tool designs

Tool design and the quality of the tool grind also have a great effect on the performance of the cutting tools. The effects of the tool design are eliminated by using a standardized tool. High speed steel tool inserts are used in conjunction with a tool holder. All the tools are first surface ground on both sides to maintain the correct thickness, and relief angle in case of all the tool bits are ground in the

same way. All the other geometries are provided in the holder. The nose radius is ground using a radius grinding attachment. The tool holder has a square shank.

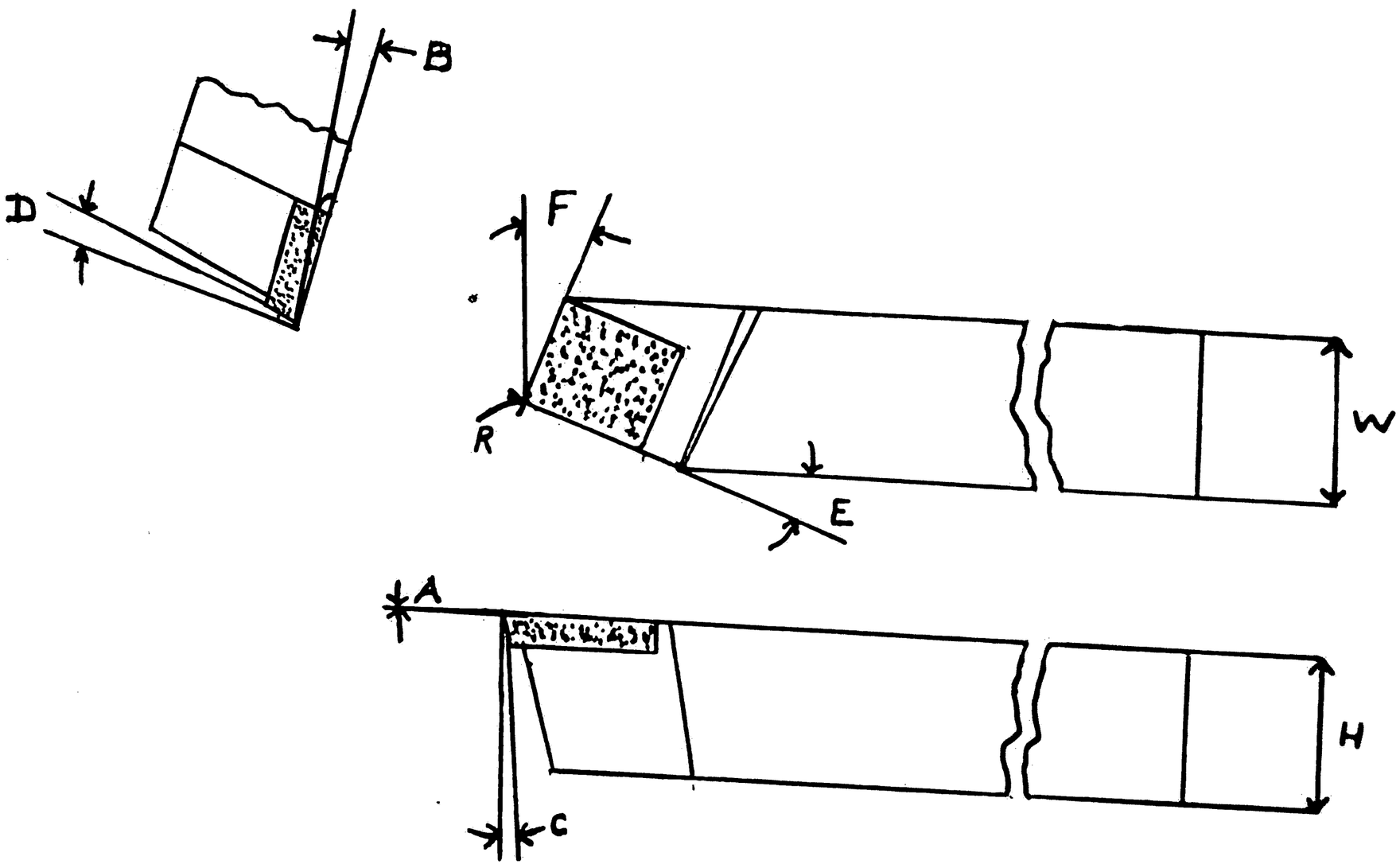
The experiment was carried out on a Lodge 14" heavy duty lathe. One end of the bar was gripped in a four jaw chuck and driven while the other end was supported on a revolving center. A varydyne motor was used in conjunction with the lathe. The varydyne motor was [illegible] lever for the lathe so that the desired values of speed ranges could be obtained. The peripheral speeds are measured using a tachometer.

The following are the actual test conditions employed.

a) The effect of work material is eliminated by using the same composition material, heat treated and obtained from the same batch of production.

b) The effects of tool design are eliminated by using a standardized tool design throughout the experimental investigation.

c) Three different cutting speeds of 100, 150 and 200 surface feet per minute, two different depths of cut, 0.05" and 0.075", and two different feed rates of 0.015 and 0.020 inch per rev. are employed and the [illegible] of crater wear on the tool insert is made after time intervals of 2 mins., 4 mins. and 8 mins. for all the combinations of the above cutting conditions. In all the cases the cutting is done dry.



Tool character

A	Back rake angle	0°
b	Side rake angle	6°
C	End relief angle	11°
D	Side relief angle	5°
E	S.C.E. A.	15°
F	E.C.E. A.	15°
R	Nose radius	3/64"

W=H=1"

Tool thickness = 3/16"

The crater wear area is measured using an optical comparator. A Jones and Lanson 20 14 model optical comparator is used for this purpose. The crater wear area of the tool insert is projected over the screen of the optical comparator after magnifying 20 times, using a 20X lens. The contour of the wear area is traced on a tracing sheet for all the combinations of cutting conditions after the time intervals of 2 mins., 4 mins. and 8 mins. A planimeter is used for the calculation of the areas. In all the cases the areas are measured 5 times and the mean area is calculated. All the cutting conditions are repeated a second time so that the average area of wear could be used for the investigation purposes. A statistical analysis is made to determine the level of significance of the various cutting parameters. A Duncan multiple range comparison test is done to group the tools to various categories as per the wear areas. The mean wear area of each group is taken (including the repetition) for the analysis purposes.

Statistical tests and results

Analysis of variance and F-tests

A computer program for the one way analysis of variance was run for the tool wear areas, and the F ratio was calculated for each cutting condition of speed, feed, depth, tool material and time. Only the first order interactions are considered in the analysis. From the F value it was found that all the first order levels, speed, feed, depth,

time and tool material have a significant effect on the tool wear with a confidence level greater than 95% in all cases. The F value is obtained by dividing the mean square values of each parameter by the mean square value within replicates. Using an F distribution table, the level of significance of each variable is found.

Duncan multiple range test (See ... page 55)

A Duncan multiple range test calculation is made to classify the tools into groups from the wear values. The Duncan multiple test gives a means of grouping the tools from their wear area values with a certain level of confidence.

Calculations

The value of mean sq. area within replicates $= s^2 = 0.02321$

$$s = \sqrt{.02321} = 0.1523$$

The number of cutting conditions employed for each kind of tool $= 3x2x2x3 = 36$

where 3 speeds, 2 feeds, 2 depths and 3 times are employed

$$s/\sqrt{36} = \frac{0.1523}{6} = \underline{0.0253}$$

Let P be the number (inclusive) of observed observations between the smallest and the largest of the P-set.

P = 7, the no. of different kinds of tools which we try to group them into category wise.

For a value of $\alpha = .01$, looking into Duncan tables, we get the values as shown in the table in Column D.

P	Percentage Duncan Point D	$s/\sqrt{36}xD$
7	3.19	0.079
6	3.15	0.078
5	3.09	0.077
4	3.02	0.075
3	2.92	0.073
2	2.77	0.069
-	-	-

Table A

Marginal means for the seven different tools from the computer program are

Tool Variables	Means
C	0.98831 ≈ 0.99
E	1.17733 ≈ 1.18
D	1.2307 ≈ 1.23
A	1.360 ≈ 1.36
G	1.4229 ≈ 1.42
F	1.5213 ≈ 1.52
	1.5849 ≈ 1.58

Case 1

For P = 7

$$1.58 - 0.99 = 0.59 > 0.079 = \frac{s}{\sqrt{36}} xD$$

For P = 6

$$1.58 - 1.18 = 0.40 > 0.078$$

$$1.52 - 0.99 = 0.53 > 0.078$$

For P = 5

$$1.58 - 1.23 = 0.35 > 0.077$$

$$1.52 - 1.18 = 0.34 > 0.077$$

$$1.42 - 0.99 = 0.43 > 0.077$$

For P = 4

1.58 - 1.36 = 0.22 > 0.075

1.52 - 1.23 = 0.29 > 0.075

1.42 - 1.18 = 0.24 > 0.075

1.36 - 0.99 = 0.37 > 0.075

For P = 3

1.58 - 1.42 = 0.16 > 0.073

1.52 - 1.36 = 0.16 > 0.073

1.42 - 1.23 = 0.19 > 0.073

1.36 - 1.18 = 0.18 > 0.073

1.23 - 0.99 = 0.24 > 0.073

For P = 2

1.58 - 1.52 = 0.06 < 0.069

1.52 - 1.42 = 0.10 > 0.069

1.42 - 1.36 = 0.06 < 0.069

1.36 - 1.23 = 0.13 > 0.069

1.23 - 1.18 = 0.05 < 0.069

1.18 - 0.99 = 0.19 > 0.069

The values of the Duncan points are taken from the Duncan tables for an α value = 0.05, for an F value > 120 i.e. (∞). These values are given in the column of Table A. The product $s/\sqrt{N} \times D$ is computed for each value of the Duncan point where s represents the square root of mean squares within replicates (gotten from the computer values) and N represents the number of variables, speed x feed x depth x time, which is 3x2x2x3 = 36.

The computation for making the grouping of the tools is done as follows.

For a value P = 7, the difference between the seventh and the first mean is calculated. If this value is greater than the value of $s/\sqrt{n} \times D$ for 7 from the Table A (which is 0.78), then these do not form a group and so don't underline this line.

In the case of P = 6, the computation is done in a similar way by finding out the difference between the means of the 7^{th} and the 2^{nd} tools and also the difference between the means of the 6^{th} and the first. These two values are compared with the value of $s/\sqrt{n} \times D$ for P = 6.

The same process of computation is carried out for all the cases of P from P = 7 to P = 2 in successive descending order. If in any case, the difference between the means of two values is less than the corresponding value of $s/\sqrt{n} \times D$, then that equation is underlined. All the underlined equations indicate that they fall into a group or category with a confidence level of 95%.

The Duncan test reveals the following facts.

Tools B and E fall into one group. Tools D and A form into a second different group and Tools G and F fall into a third seperate group. Tool C does not fall into any one of the groups and stands independently as a group by itself.

Arranging the tools by ranks of wear properties, we have the following classification.

Tool Designation	Rank
C	1
E and B	2
D and A	3
G and F	4

The ranking is done on the basis of increasing order of wear. From the table shown above, we see that Tool C stands independent while Tools E and B, D and A and G and F form three seperate groups. So the average wear areas for each group for each cutting condition is calculated for different cutting times and a graph is plotted for the average wear against the time for various cutting conditions. All the cutting is duplicated and the average areas in each case are taken for the experiment and its repetition.

Discussion of Results

Initially, the experiment was started with an idea of measuring the flank land wear to determine the machinability performance index of the tool, using a finish cutting condition without using a cutting fluid. So obviously a measurement of the surface finish on the work material was made. The several test runs made indicated that the tool failed mainly due to the crater wear rather than the flank wear for the above cutting conditions. The measurement of flank land wear led to a blind path. So the experiment was switched over

to the measurement of crater wear. A rough cutting condition was employed. The measurement of change in dimension of the work material was made and the measurement of surface finish was dropped because of the roughing conditions. Since the noted variations in the dimensions were not appreciable and were well within the limits of the tolerance level for a roughing cut, this also was not analyzed.

Graphs are plotted with the average crater wear Vs time for each group of tools for several cutting conditions. From the statistical analysis we see that the speed has the greatest effect on the wear of the tool followed by depth, feed and tool material in order of preference. These graphs help us to compare the performance criteria of the different kinds of tools. The table shown below gives the values of the average amount of retained austenite, average amount of carbide content and the average hardness value of the various groups of tools. A Duncan multiple range statistical test is done to group the tools in the order shown below.

Tool Designation	Avg. % vol. fraction of Retained Austenite	Avg. % vol. fraction of Carbide	Hardness Rc
Group C	8.56%	37%	63.8
Group B & E	13.15%	33.3%	63.2
Group D & A	16.31%	30.3%	62.5
Group G & F	20.1%	24.4%	62.1

From the graphs we see that the Tool C stands foremost in the rating followed by Group B and E, Group D and A and by Group G and F, ranking them in order of the crater wear.

The table shown on the preceding page enables us to make the following conclusions.

Tool C has the lowest average amount of volume fraction of retained austenite, (8.56%) and the highest amount of percentage volume fraction of carbide of 37%. The average hardness is 63.8. This tool ranks the best among the various groups that are compared.

Tool group B and E ranks the second in order which has 13.15% of average volume fraction of retained austenite, 33.3% of average volume fraction of carbide and a hardness of 63.2.

Tool C has a greater amount of carbide content, a lesser amount of retained austenite and a higher hardness as compared to the Group B and E. Tool C shows a better wear resistant property compared to Group E and F.

A Similar comparison can be made for [illegible] and also for Group G and F. This will [illegible] indicate that the Group D and A ranks the third and Group G and F ranks fourth in order of performance.

Tool C, which has the lowest amount of retained austenite has the highest hardness number of 63.8 Rc. The smaller the amount of retained austenite, the greater is the amount of martensite in the resulting structure. Martensite being the hardest constituent in the phase, explains the slight increase in the hardness. An increase in hardness increases the wear resistance property of the tool. The

major thing that gives the tool the wear resistant property is the volume percentage of excess carbide. The higher the amount of these excess carbides, the greater will be the wear resistance of the tool. It is only these carbides that make the high speed steels superior to the high carbon steels which can be also heat treated to the same hardness value.

In the case of tools B and C we see that they are given the same kind of heat treatment (page 22) but with a very slight change in cryogenic cooling. The tool C is treated cryogenically to 2 cycles while the tool B is cooled only to one cycle cryogenically. We see a slight increase in hardness of the tool C over that of tool B by 0.8 points on the Rc scale. Also, the carbide content of the tool C is higher than that of B. These two are mainly responsible for the superiority of the tool C over that of B. Also, tool C has less retained austenite as compared to tool B. The lower the amount of retained austenite, the lower will be the amount of transformation of retained austenite into martensite due to aging. Also this transformation is accompanied by an increase in volume of about 4 to 5%.[8] This sets up surface and residualstress on the material. Sometimes even an actual change in dimension takes place due to this increase in volume. Due to these reasons it is always desirable to have a tool with the lowest amount of the retained austenite. The table gives the values of the amount of the retained

austenite, carbide percentage and the hardness number on the Rc scale. We see that the tool with the lowest amount of retained austenite has the highest hardness and a higher amount of carbide content.

Also, we see that two tempering operations are better than one and that the cryogenic treatment does not replace the second tempering operation.

Similarly, we see for tools D and E, E has a higher hardness, 63.3 Rc, as compared to that of D, 62.6 Rc. Tool D is cryogenically cooled only once whereas tool E is treated cryogenically twice, while all the other heat treating conditions remain the same. We see that the one extra cryogenic treating cycle has increased the hardness of tool E by 0.7 Rc points as against that of tool D. Also, the carbide content of tool E is higher than that of D and the volume fraction of retained austenite of tool E is less than that of tool D. Tool E ranks superior to tool D as per the wear resistance property.

In the same way we see that in the case of tool C, which is cryogenically cooled to 2 cycles as against that of F, which is treated cryogenically only once, we see an increase in hardness of 0.2 points Rc in the case of tool C.

All the above figures indicate that the tools that are treated cryogenically to two cycles are better than the tool that is treated only once. Also, tool C, which has a double tempering operation and two cryogenic cooling cycles is

better than all the other tools compared. So we see that the two tempering operations give the tool a better wear property (due to secondary hardness), compared to one tempered only one time.

Conclusion

From the above discussion we can conclude that a high speed steel tool which is cryogenically treated has a better wear resistance property than one which is not cryogenically treated. This of course is due to the fact that cryogenic treatment transforms a portion of the retained austenite into martensite. Also, the cryogenic treatment increases the hardness of the tool by a few points. The tool which is cryogenically treated twice has a greater hardness and better wear resistance property than one which is cryogenically treated only once. The tool which is tempered twice and treated cryogenically for a given cycle is better than the one which is tempered only once and then cryogenically treated for the same number of cycles. This is due to the fact that the second tempering operation gives greater hardness to the tool due to secondary hardening.

The cryogenic treatment cannot be substituted for the second tempering operation. From the graphs we see that the tool with two tempering operations plus cryogenic treatment stands the best in the wear resistance property. Since all the high speed steel tools are double tempered commercially, these can be straightaway treated cryogenically to increase

the wear resistance properties.

Areas where this can be applied

High speed steels are becoming more and more obsolete as a single point tool because of the entrance of the many newly developed materials such as carbides, ceramics, aluminum oxide tools etc. But high speed steel is still popular in many of the metal machining applications such as drills, reamers, taps, milling cutters, [illegible], and several other farm tools. All these tools are generally commercially available after a double temper treatment. We can treat these tools cryogenically to increase the life of the tools even as much as 150 to 200% in some cases. A study conducted by the Sperry Rand Corporation for Louisiana Army Ammunition Plant[27] discloses the following interesting figures.

Items	Service type	Avg. life before Treatment	After Treatment	Factor Increase
end mill	wear	65 parts	200 parts	3.07
hacksaw blade	wear	4 hrs.	6 hrs.	1.5
zone punches	impact	64 parts	5280 parts	82.5
thread dies	wear	225 parts	487 parts	2.2

The above are only a few of the items they have studied and we see from this that the cryogenic treatment of the tool really has a tremendous effect upon the improvement on the performance index of a tool.

Areas recommended for future study

All the experiments discussed in the preceding paragraphs are done for a rough cutting condition using no cutting fluids. The measured parameter is crater wear area. The same experiment could be done using a cutting fluid which is more realistic in production conditions. Also, the measurement of flank land wear for a finish cutting condition using a coolant can be made. It is inferred from the experiment that the tool cryogenically treated has a better wear resistance than a tool not treated likewise. So the effect of surface finish on the work material due to cryogenic treatment on a tool can be studied. This study may be especially more suitable in the case of plunge forming tools. Also, an interrupted cutting can be used on a turning job to study the edge strength of a cryogenically treated tool. Similarly, the wear characteristics of a punch in a sheet metal operation can be studied both in the case of high speed steel as well as high carbon steel.

In all the studies made under investigation, T 15 grade of high speed steel was used. To study the effects of the alloying elements a molybdenum base tool can be used instead of a tungsten base tool.

Also, the experiment reveals that a tool which is cryogenically treated twice has a much better wear resistance than one which is treated cryogenically only once for the same heat treatment. A study can be made by actually

increasing the cryogenic treating cycles and to obtain an optimum number of cycles to get the best wear resistance of the tool.

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APPENDICES

Tool Group C

Speed s.f.p.m.	Depth in.	Feed per rev.	Crater wear area in sq. in. for Tool C			Average crater wear area in sq. in. for Tool C		
			2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.
100	0.05	0.015	0.364 0.406	0.528 0.496	0.634 0.688	0.385	0.512	0.661
100	0.05	0.020	0.428 0.502	0.662 0.588	0.746 0.792	0.465	0.625	0.769
100	0.075	0.015	0.652 0.524	0.704 0.608	0.782 0.698	0.588	0.656	0.740
100	0.075	0.020	0.680 0.708	1.080 0.956	1.220 1.286	0.694	1.018	1.253
150	0.05	0.015	0.702 0.796	0.804 0.882	0.872 0.942	0.749	0.843	0.907
150	0.05	0.020	0.824 0.868	0.936 1.076	1.158 1.106	0.846	1.006	1.132
150	0.075	0.015	0.906 1.074	1.084 1.108	1.236 1.192	0.990	1.096	1.214
150	0.075	0.020	0.992 1.216	1.226 1.442	1.374 1.522	1.104	1.334	1.448
200	0.05	0.015	0.766 0.812	1.004 0.898	1.174 0.998	0.789	0.951	1.086
200	0.05	0.020	0.932 0.854	1.154 0.978	1.242 1.072	0.893	1.066	1.157
200	0.075	0.015	1.038 0.972	1.338 1.258	1.602 1.524	1.005	1.298	1.563
200	0.075	0.020	1.208 1.352	1.430 1.374	2.034 2.014	1.280	1.402	2.098

All the areas shown are for 20X magnification.

Tool Group D&A

Speed sfpm	Depth in.	Feed per rev.	Crater wear area in sq. in. for Tool D			Crater wear area in sq. in. for Tool A			Avg. Crater wear area in sq. in. Group D&A		
			2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.
100	0.05	0.015	0.450 0.420	0.672 0.656	0.876 0.952	0.480 0.402	0.704 0.782	0.952 0.856	0.438	0.703	0.909
100	0.05	0.020	0.640 0.712	0.802 0.842	1.052 0.992	0.636 0.762	0.764 0.798	1.192 1.121	0.688	0.802	1.086
100	0.075	0.015	0.724 0.672	0.796 0.656	1.220 1.040	0.624 0.748	0.780 0.824	1.204 1.266	0.692	0.764	1.183
100	0.075	0.020	0.856 0.796	1.178 1.094	1.484 1.366	1.092 1.116	1.244 1.218	1.552 1.476	0.965	1.183	1.469
150	0.05	0.015	0.872 0.836	0.974 1.020	1.174 1.180	0.948 0.854	1.042 0.901	1.312 1.269	0.878	0.984	1.234
150	0.05	0.020	1.032 1.004	1.220 1.292	1.542 1.636	1.042 1.126	1.264 1.314	1.602 1.719	1.051	1.272	1.625
150	0.075	0.015	1.260 1.364	1.424 1.522	1.794 1.652	1.380 1.278	1.796 1.641	1.992 1.786	1.321	1.596	1.806
150	0.075	0.020	1.882 1.802	2.064 2.002	2.164 2.202	1.860 1.742	2.052 1.984	2.142 2.246	1.821	2.025	2.189
200	0.05	0.015	1.002 1.178	1.252 1.324	1.372 1.508	1.196 1.224	1.338 1.412	1.496 1.564	1.150	1.332	1.485
200	0.05	0.020	1.166 1.202	1.344 1.500	1.684 1.760	1.264 1.312	1.384 1.572	1.752 1.788	1.236	1.450	1.745
200	0.075	0.015	1.664 1.642	1.904 1.988	2.256 2.364	1.796 1.682	1.892 1.914	2.308 2.416	1.671	1.899	2.336
200	0.075	0.020	1.784 1.602	2.324 2.202	3.034 3.002	1.752 1.602	2.384 2.416	3.164 3.124	1.685	2.332	3.093

All the areas shown are for 20x magnification.

Tool Group B&E

Speed sfpm	Depth in.	Feed per rev.	Crater wear area in sq. in. for Tool B			Crater wear area in sq. in. for Tool E			Avg. Crater wear area in sq. in. Group B&E		
			2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.
100	0.05	0.015	0.404 0.432	0.598 0.522	0.738 0.784	0.436 0.396	0.574 0.502	0.842 0.768	0.418	0.549	0.783
100	0.05	0.020	0.444 0.512	0.670 0.734	0.862 0.904	0.628 0.560	0.696 0.736	1.042 0.816	0.536	0.709	0.906
100	0.075	0.015	0.612 0.552	0.758 0.676	0.854 0.798	0.616 0.624	0.802 0.904	0.924 0.976	0.601	0.785	0.888
100	0.075	0.020	0.826 0.864	1.112 0.986	1.252 1.314	0.784 0.816	1.104 1.122	1.364 1.442	0.823	1.081	1.343
150	0.05	0.015	0.842 0.866	0.972 0.880	0.992 1.104	0.824 0.802	0.986 0.900	1.144 0.996	0.834	0.935	1.059
150	0.05	0.020	0.964 0.992	1.204 1.260	1.232 1.314	1.042 0.992	1.242 1.212	1.266 1.398	0.998	1.230	1.303
150	0.075	0.015	1.100 1.064	1.212 1.284	1.476 1.506	1.124 1.162	1.234 1.292	1.684 1.722	1.113	1.256	1.594
150	0.075	0.020	1.664 1.552	1.924 1.836	2.116 2.156	1.572 1.606	1.902 1.878	2.004 1.942	1.598	1.885	2.079
200	0.05	0.015	0.904 0.962	1.002 0.974	1.212 1.226	0.816 0.904	0.992 0.974	1.284 1.382	0.897	0.986	1.276
200	0.05	0.020	0.938 0.972	1.212 1.172	1.382 1.466	1.012 0.984	1.316 1.346	1.634 1.598	0.976	1.262	1.520
200	0.075	0.015	1.110 1.042	1.424 1.518	1.868 1.804	1.136 1.166	1.578 1.604	1.898 1.996	1.114	1.531	1.892
200	0.075	0.020	1.604 1.762	2.064 2.158	2.672 2.598	1.804 1.716	2.308 2.192	2.478 2.824	1.722	2.181	2.643

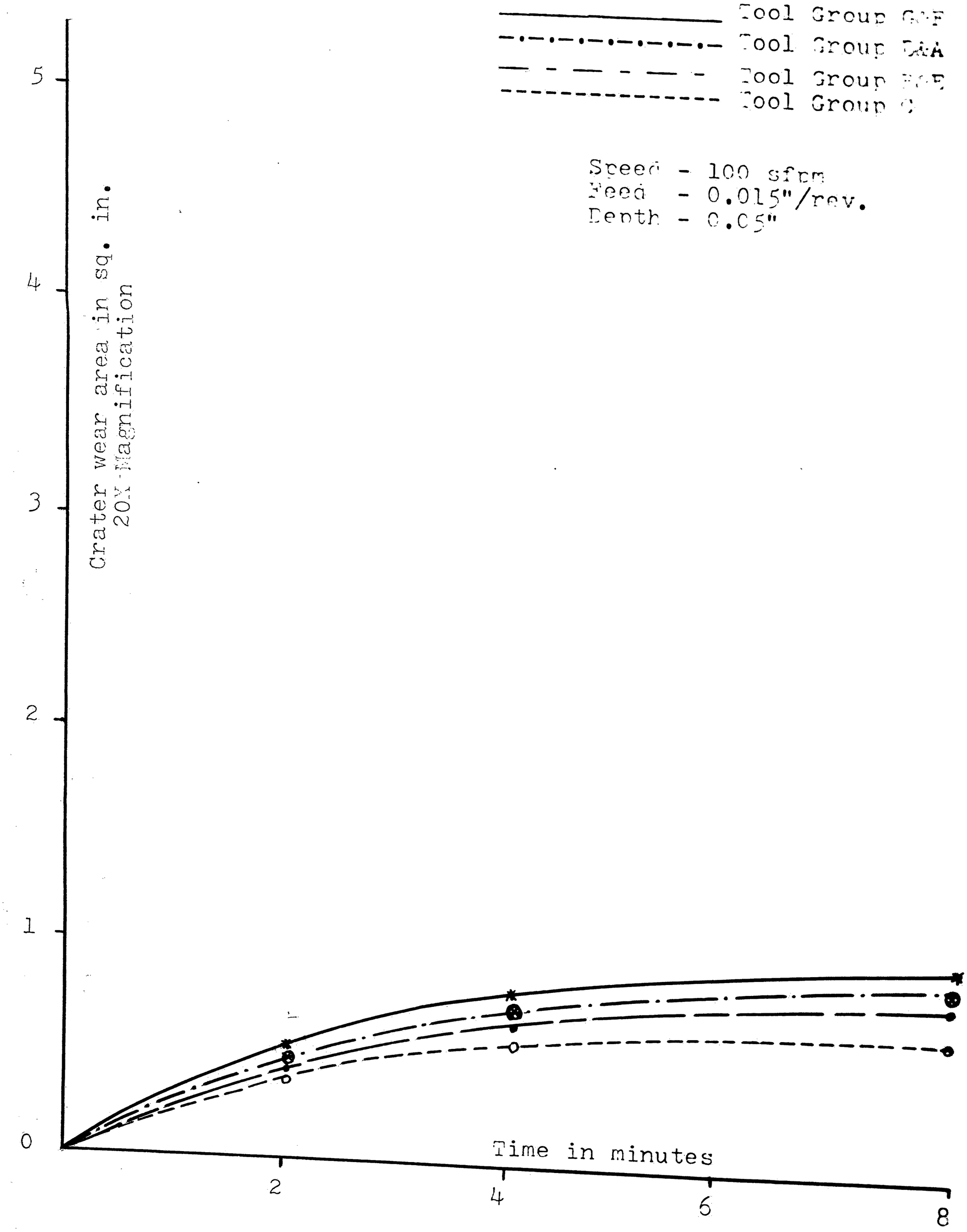
All the areas shown are for 20X magnification.

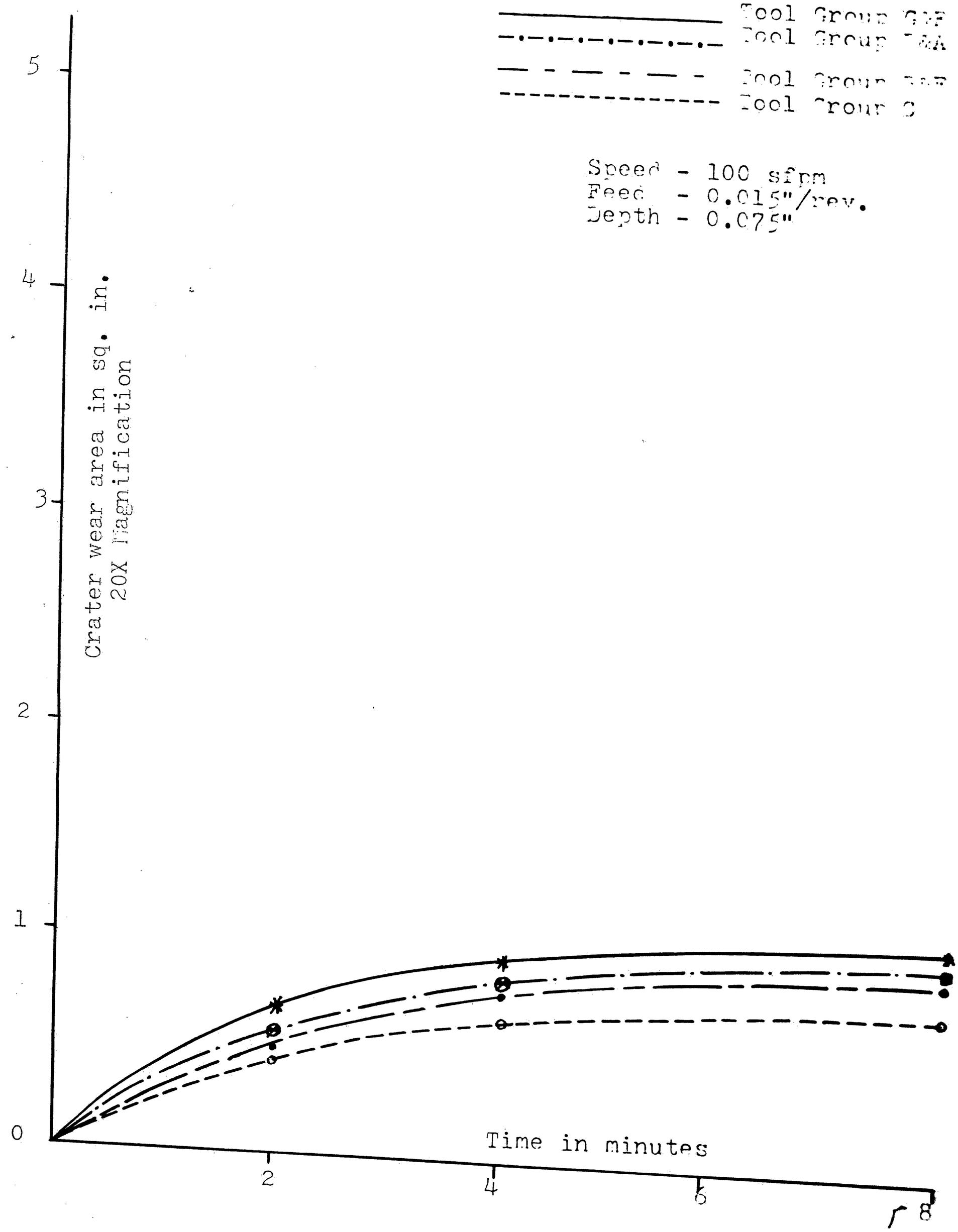
Tool Group G&F

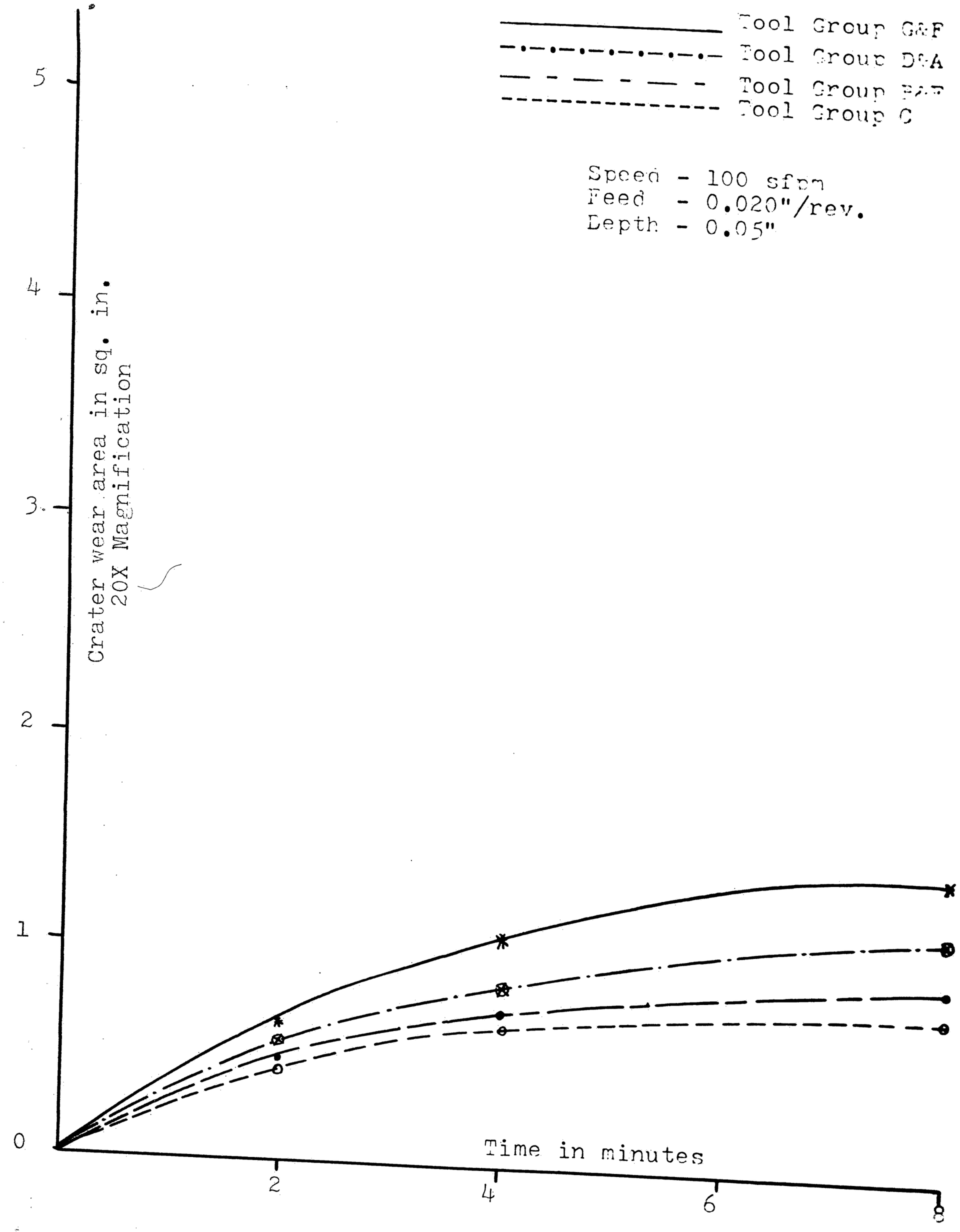
Speed sfpm	Depth in.	Feed per rev.	Crater wear area in sq. in. for Tool G			Crater wear area in sq. in. for Tool F			Avg. Crater wear area in sq. in. Group G&F		
			2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.	2 mins.	4 mins.	8 mins.
100	0.05	0.015	0.560 0.536	0.730 0.652	0.792 0.988	0.578 0.450	0.800 0.858	1.020 0.962	0.531	0.760	0.940
100	0.05	0.020	0.586 0.564	0.996 1.074	1.256 1.418	0.724 0.702	1.150 1.110	1.466 1.392	0.644	1.082	1.383
100	0.075	0.015	0.604 0.518	0.792 0.728	1.010 1.080	0.610 0.512	0.738 0.832	1.064 1.112	0.561	0.772	1.067
100	0.075	0.020	1.206 1.122	1.452 1.370	1.636 1.496	1.114 1.160	1.374 1.364	1.672 1.608	1.150	1.390	1.603
150	0.05	0.015	1.064 1.084	1.262 1.244	1.356 1.462	1.256 1.200	1.312 1.326	1.456 1.442	1.151	1.286	1.429
150	0.05	0.020	1.344 1.084	1.406 1.462	1.684 1.762	1.028 1.110	1.336 1.308	1.622 1.700	1.142	1.378	1.692
150	0.075	0.015	1.216 1.284	1.646 1.796	1.898 2.052	1.304 1.464	1.928 1.978	2.406 2.248	1.332	1.812	2.151
150	0.075	0.020	1.722 1.484	2.360 2.422	2.236 2.436	1.904 1.642	2.120 2.240	2.432 2.684	1.688	2.296	2.447
200	0.05	0.015	1.140 1.206	1.384 1.336	1.498 1.464	1.254 1.278	1.370 1.428	1.602 1.692	1.219	1.379	1.564
200	0.05	0.020	0.978 1.274	1.572 1.396	1.640 1.712	1.252 1.216	1.492 1.388	1.782 1.806	1.180	1.462	1.735
200	0.075	0.015	1.626 1.704	1.996 2.124	2.572 2.464	1.582 1.538	2.002 2.282	2.474 2.576	1.637	2.101	2.522
200	0.075	0.020	1.724 1.792	2.728 2.602	* 3.674	1.714 1.924	2.602 **7.0	4.094	1.789	3.483	4.994

All areas shown are for 20X magnification.

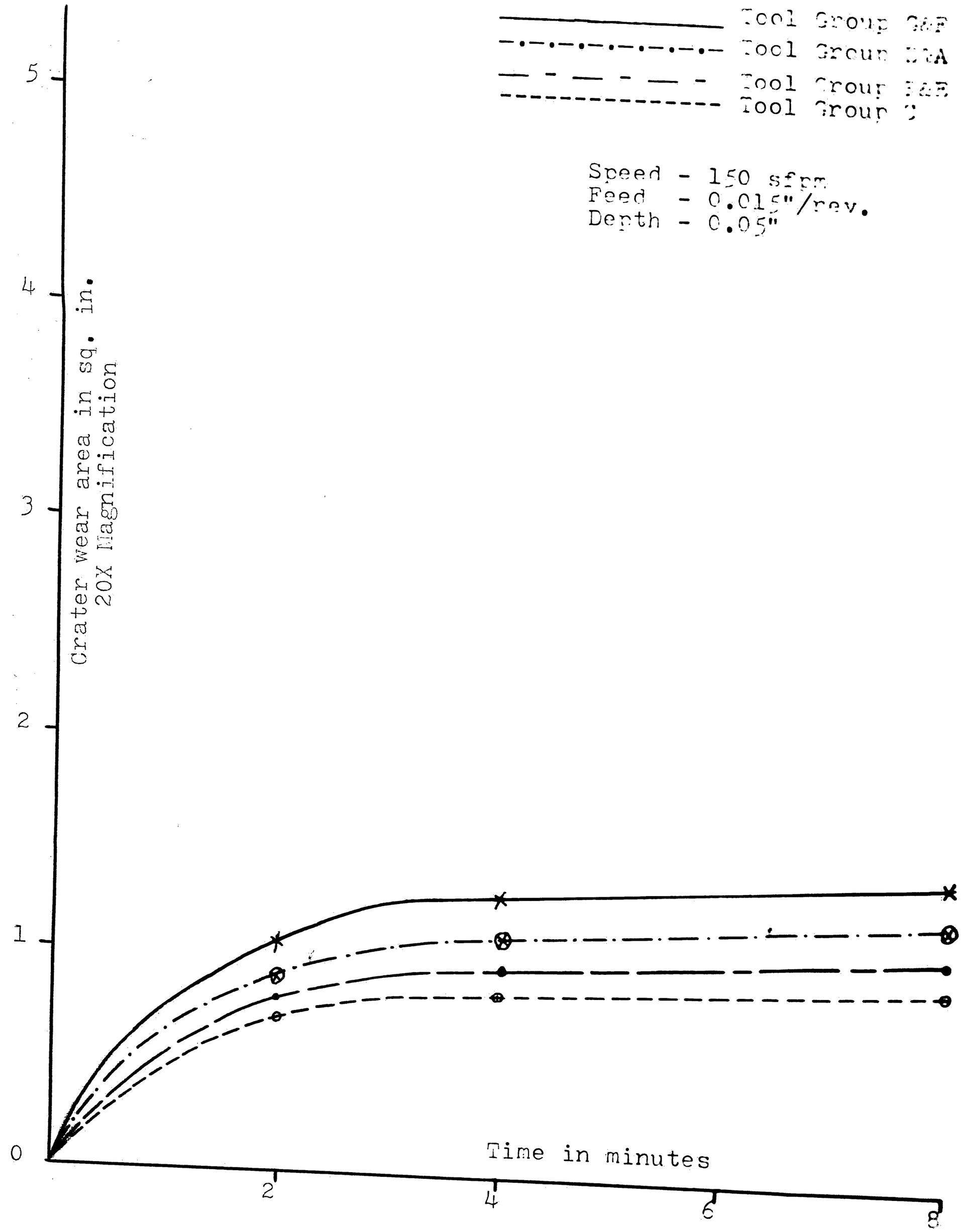
*Total tool failure after 7 min. 44 sec.
**Total tool failure after 4 min. 52 sec.

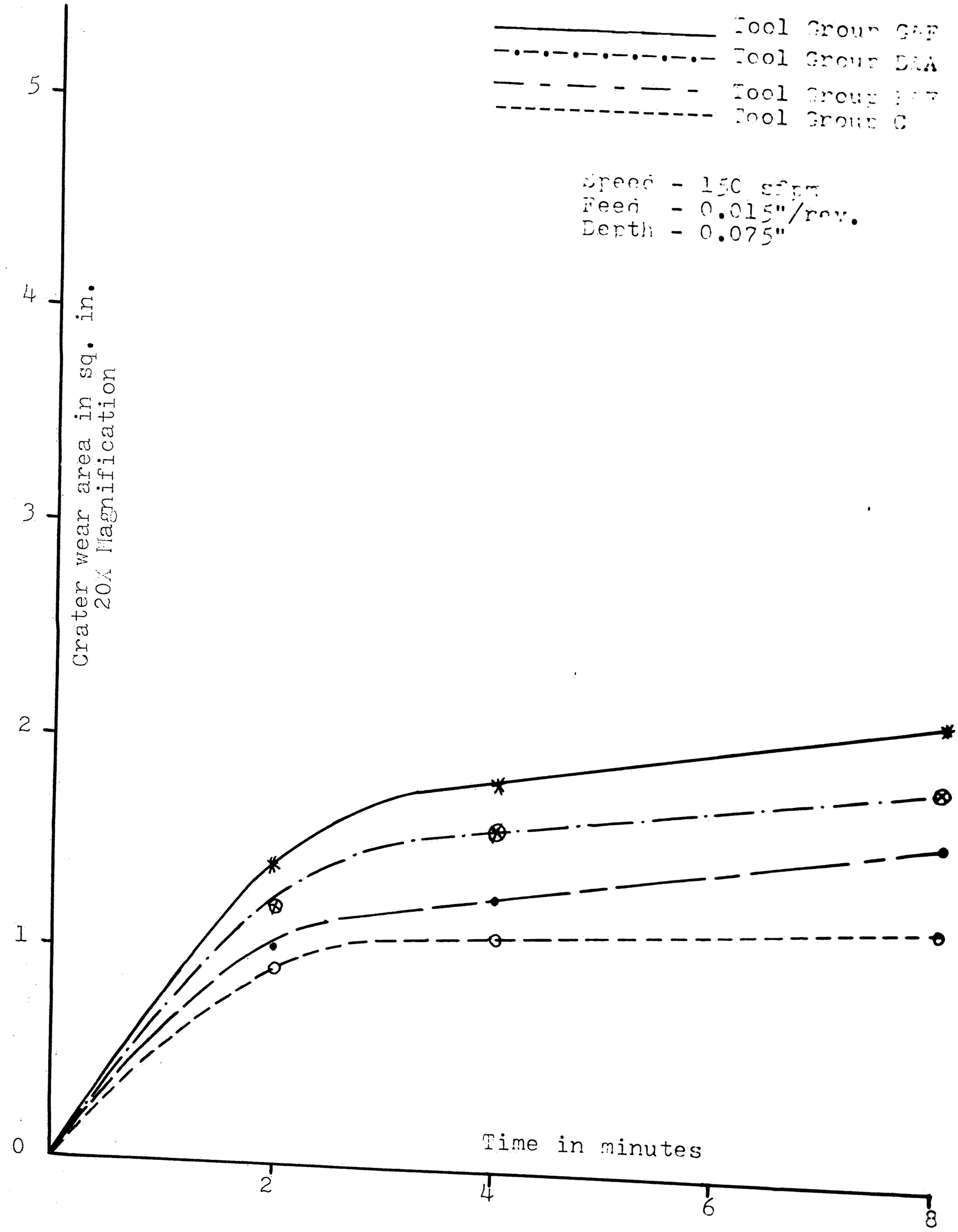

Tool Group G-F
Tool Group D-A
Tool Group B-E
Tool Group C
Speed - 100 sfpm
Feed - 0.015"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
Time in minutes
2
4
6
8

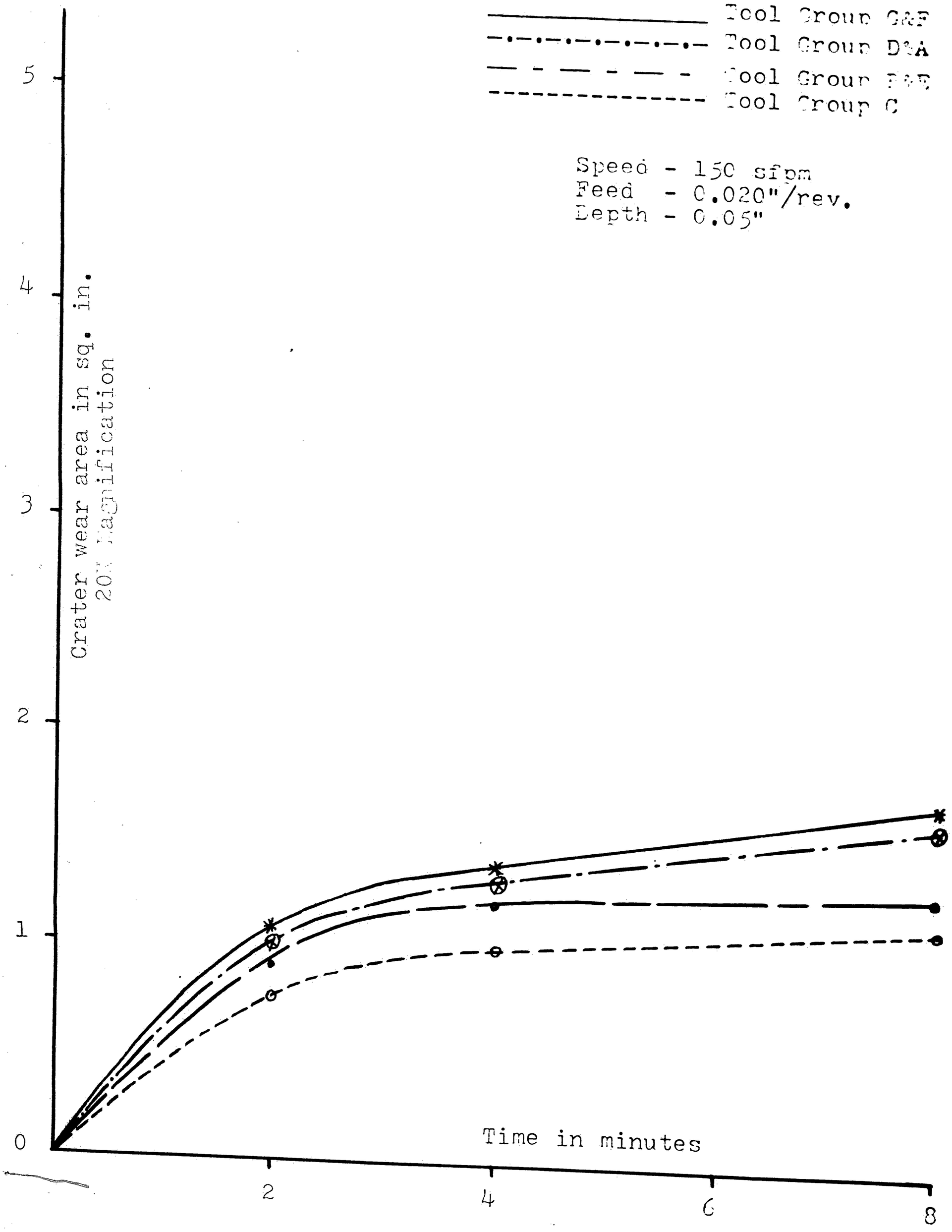

Tool Group GAF
Tool Group GAA
Tool Group GAB
Tool Group C
Speed - 100 sfpm
Feed - 0.015"/rev.
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
Time in minutes
2
4
6
8

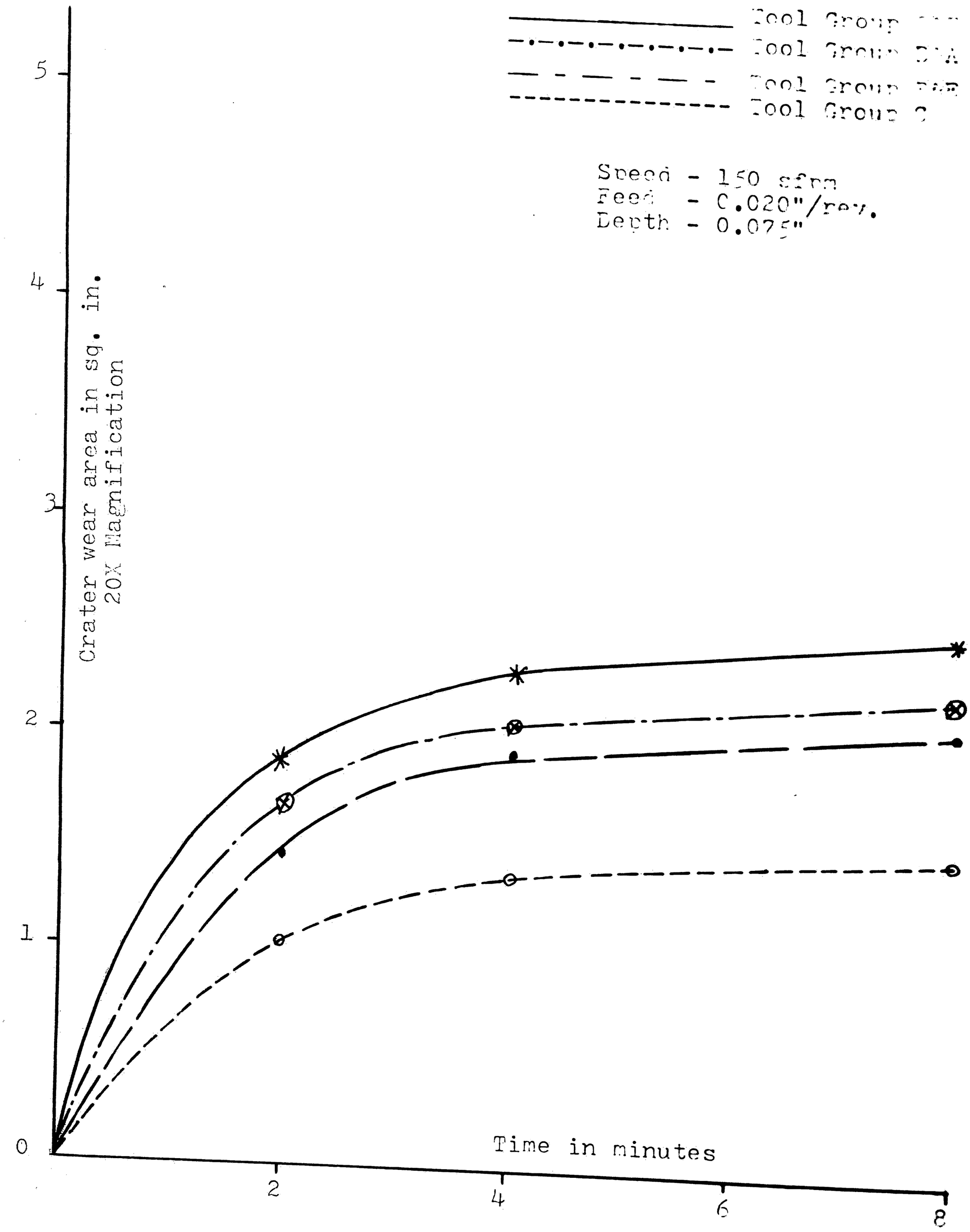

Tool Group G&F
Tool Group D&A
Tool Group B&E
Tool Group C
Speed - 100 sfpm
Feed - 0.020"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
2
4
6
8
Time in minutes

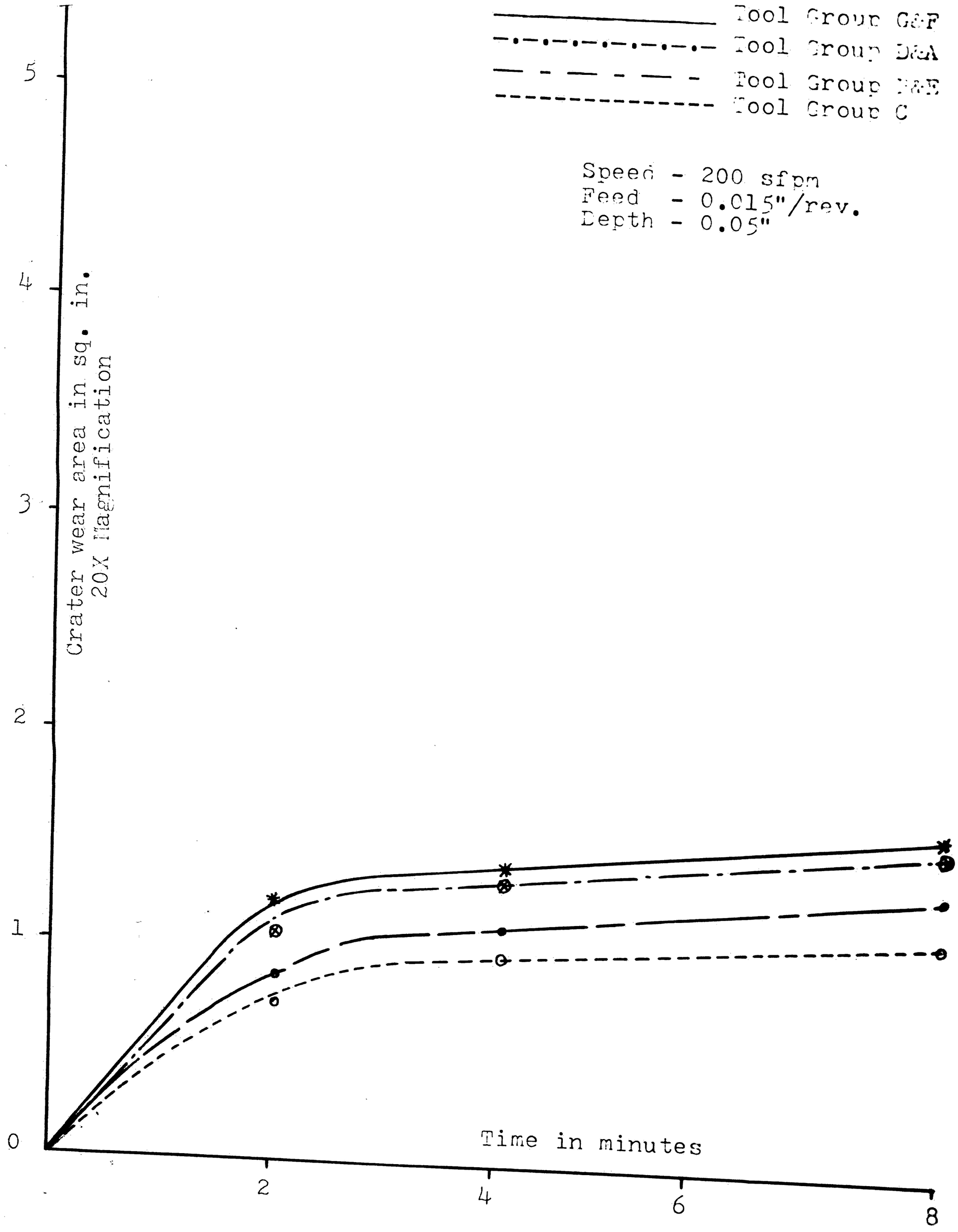
Tool Group G&F
Tool Group D&A
Tool Group B&E
Tool Group C
Speed - 100 sfpm
Feed - 0.020"/rev.
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
2
4
6
8
Time in minutes

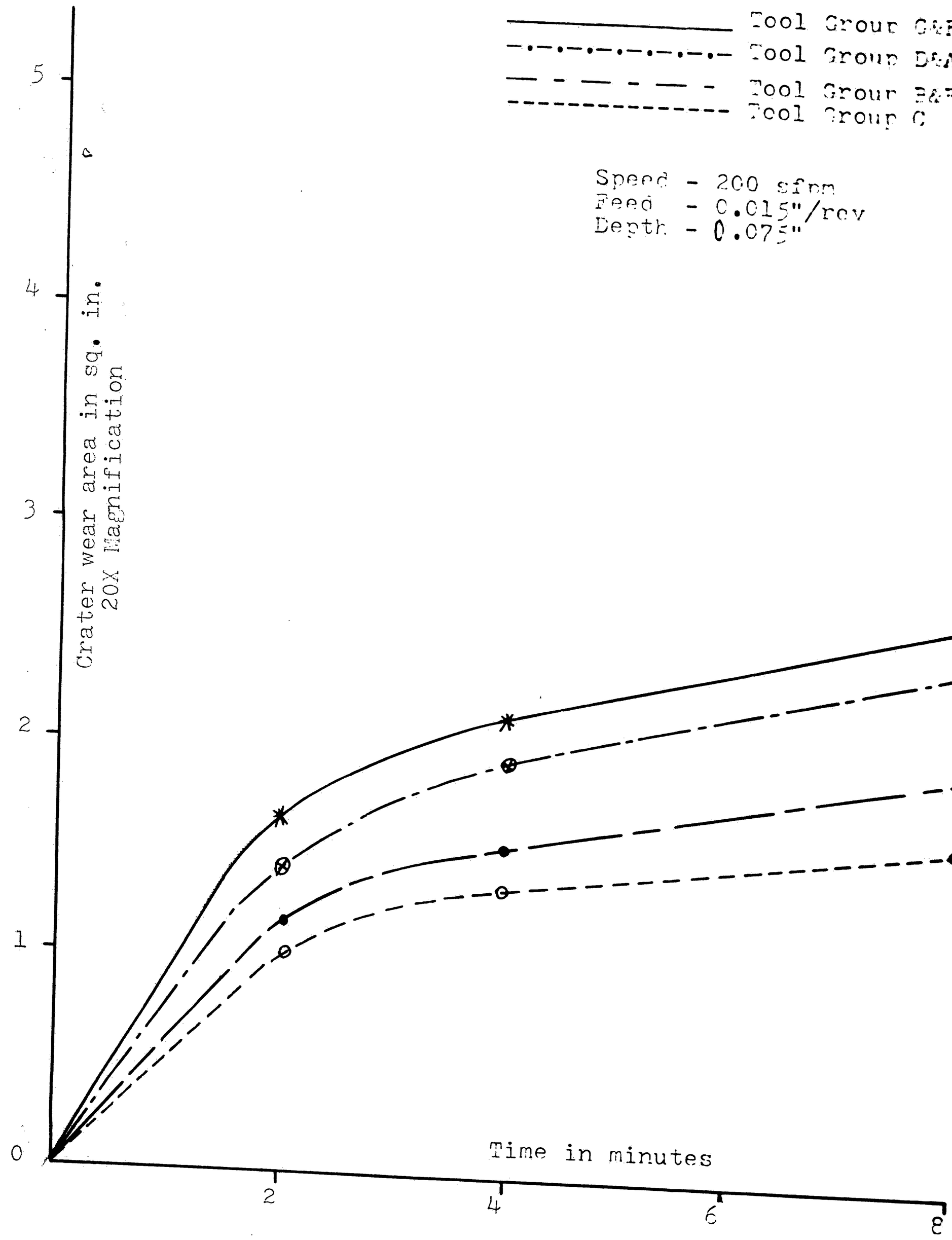

Tool Group G&F
Tool Group D&A
Tool Group B&E
Tool Group C
Speed - 150 sfpm
Feed - 0.015"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
Time in minutes
2
4
6
8

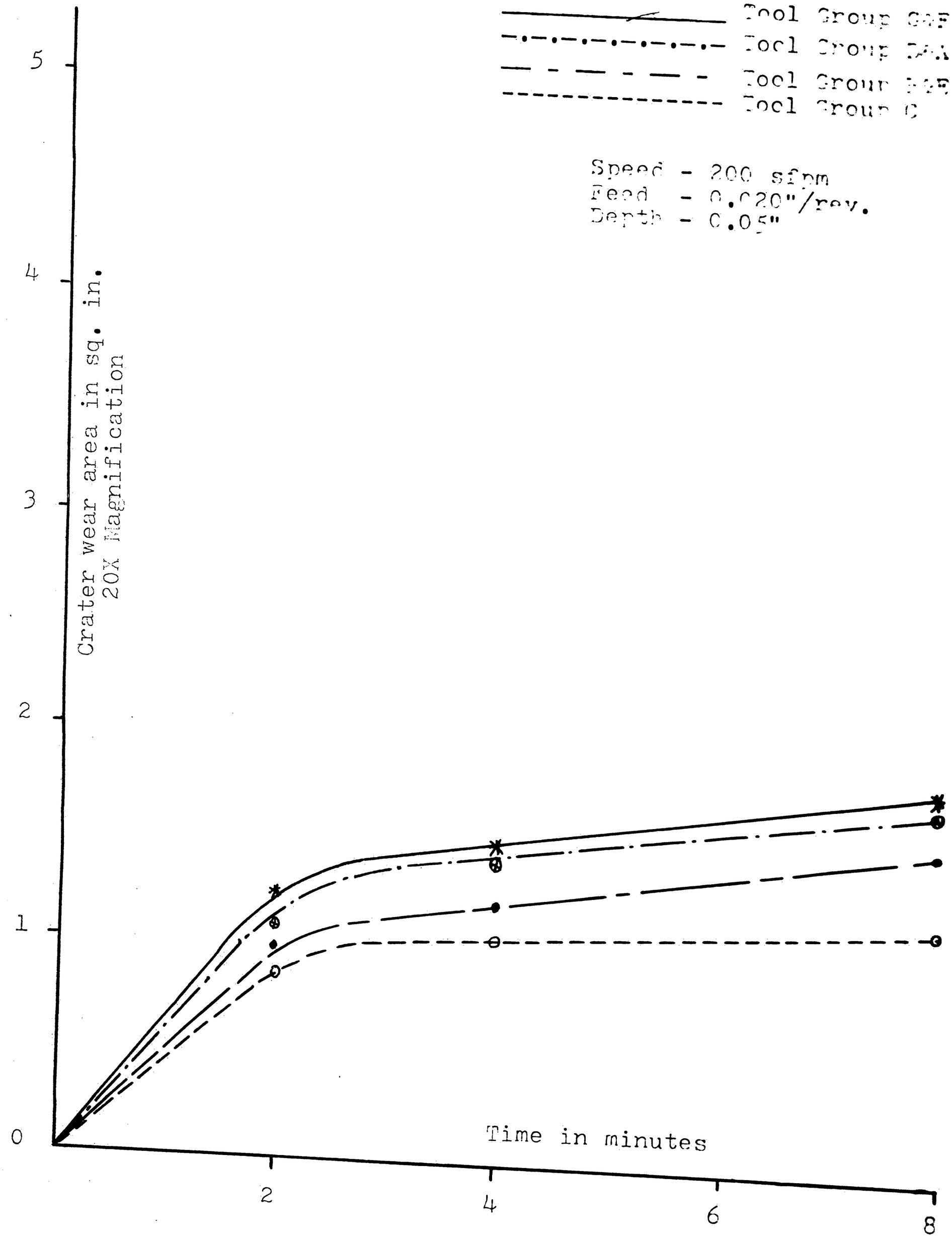

Tool Group GAF
Tool Group DAA
Tool Group
Tool Group C
Speed - 150 sfpm
Feed - 0.015"/rev.
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
2
4
6
8
Time in minutes

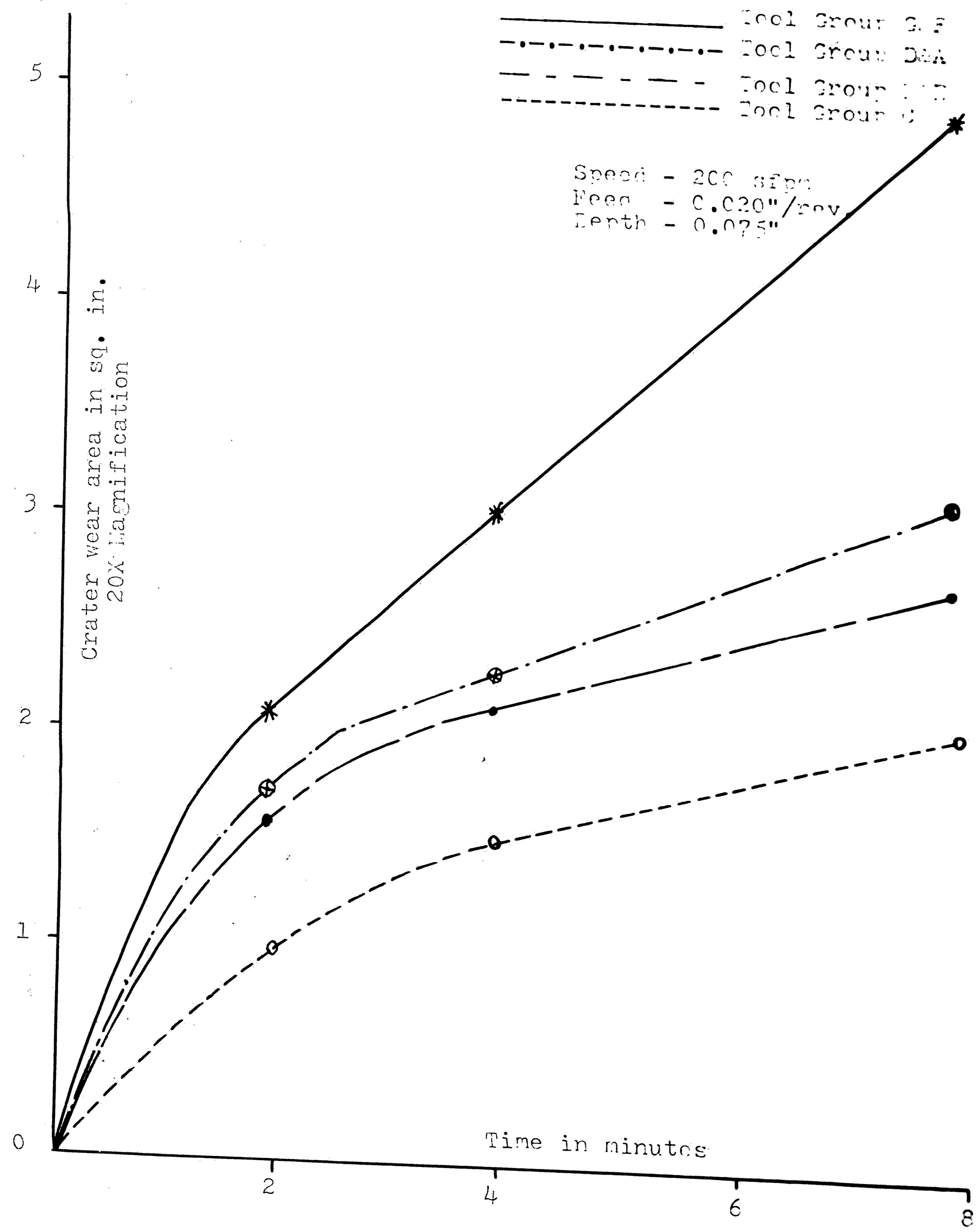

Tool Group G&F
Tool Group D&A
Tool Group B&E
Tool Group C
Speed - 150 sfpm
Feed - 0.020"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
Time in minutes
2
4
6
8

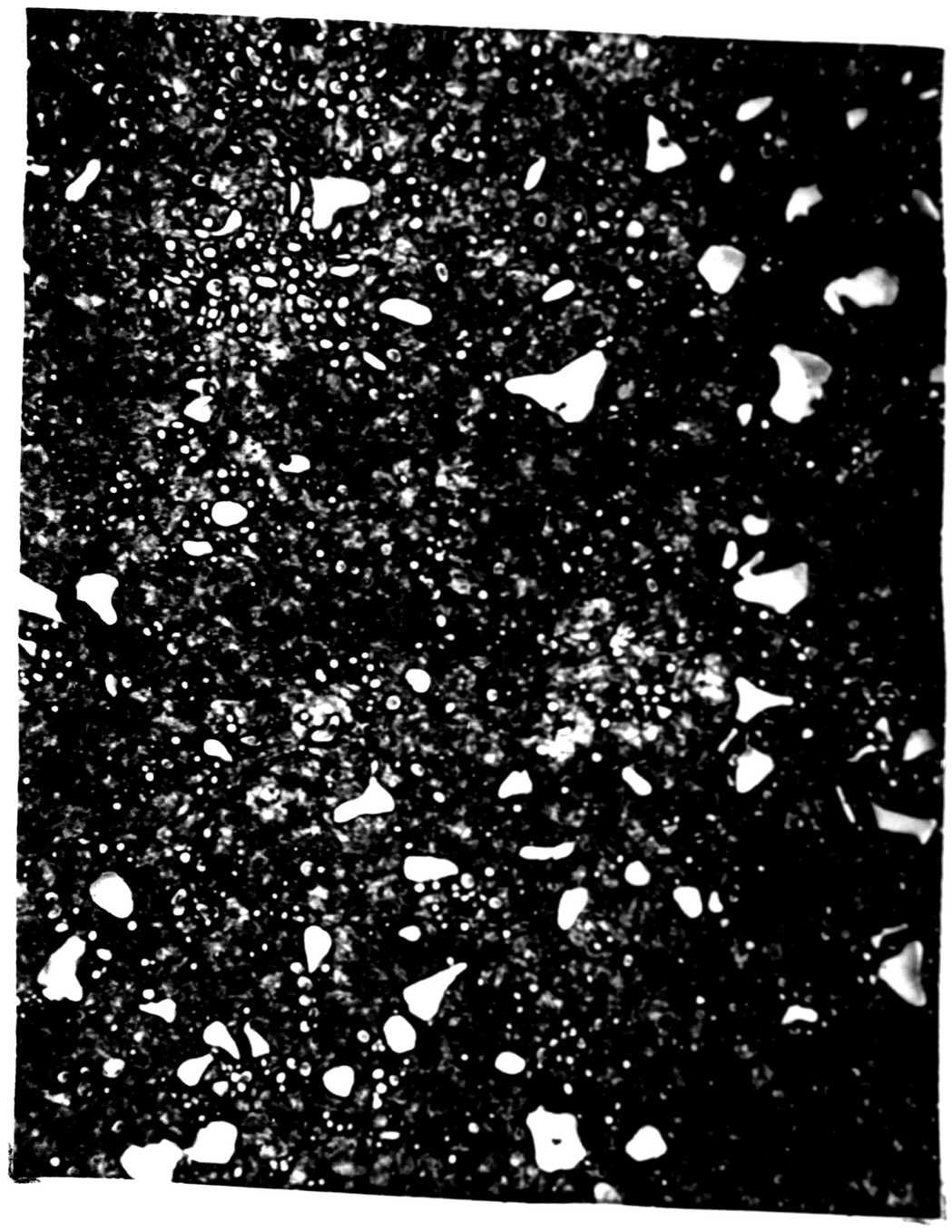

Tool Group
Tool Group
Tool Group
Tool Group C
Speed - 150 sfm
Feed - 0.020"/rev.
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
5
4
3
2
1
0
Time in minutes
2
4
6
8


Tool Group G&F
Tool Group D&A
Tool Group B&E
Tool Group C
Speed - 200 sfpm
Feed - 0.015"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
Time in minutes
2
4
6
8


Tool Group C&F
Tool Group D&A
Tool Group B&F
Tool Group C
Speed - 200 sfpm
Feed - 0.015"/rev
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
Time in minutes
2
4
6
8


Tool Group
Tool Group
Tool Group
Tool Group C
Speed - 200 sfpm
Feed - 0.020"/rev.
Depth - 0.05"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
Time in minutes
2
4
6
8


Tool Group
Tool Group
Tool Group
Tool Group
Speed - 200 sfpm
Feed - 0.020"/rev.
Depth - 0.075"
Crater wear area in sq. in.
20X Magnification
0
1
2
3
4
5
Time in minutes
2
4
6
8



Micro structure photograph of
Tool A etched in nitol solution

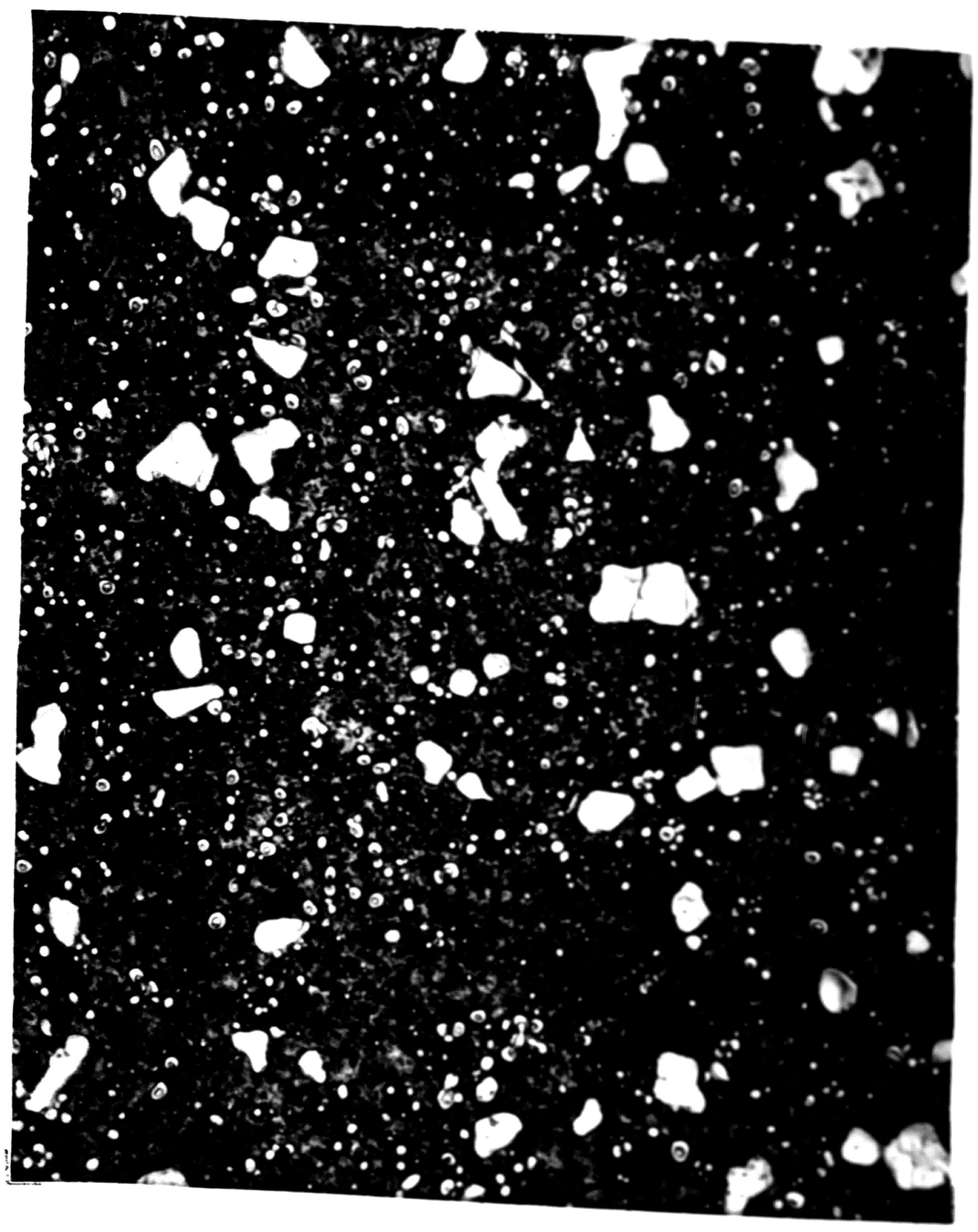
Magnification - 500X
Exposure time - 60 sec.

Micro structure photograph of
Tool B etched in nitol solution

Magnification - 500X
Exposure time - 60 sec.

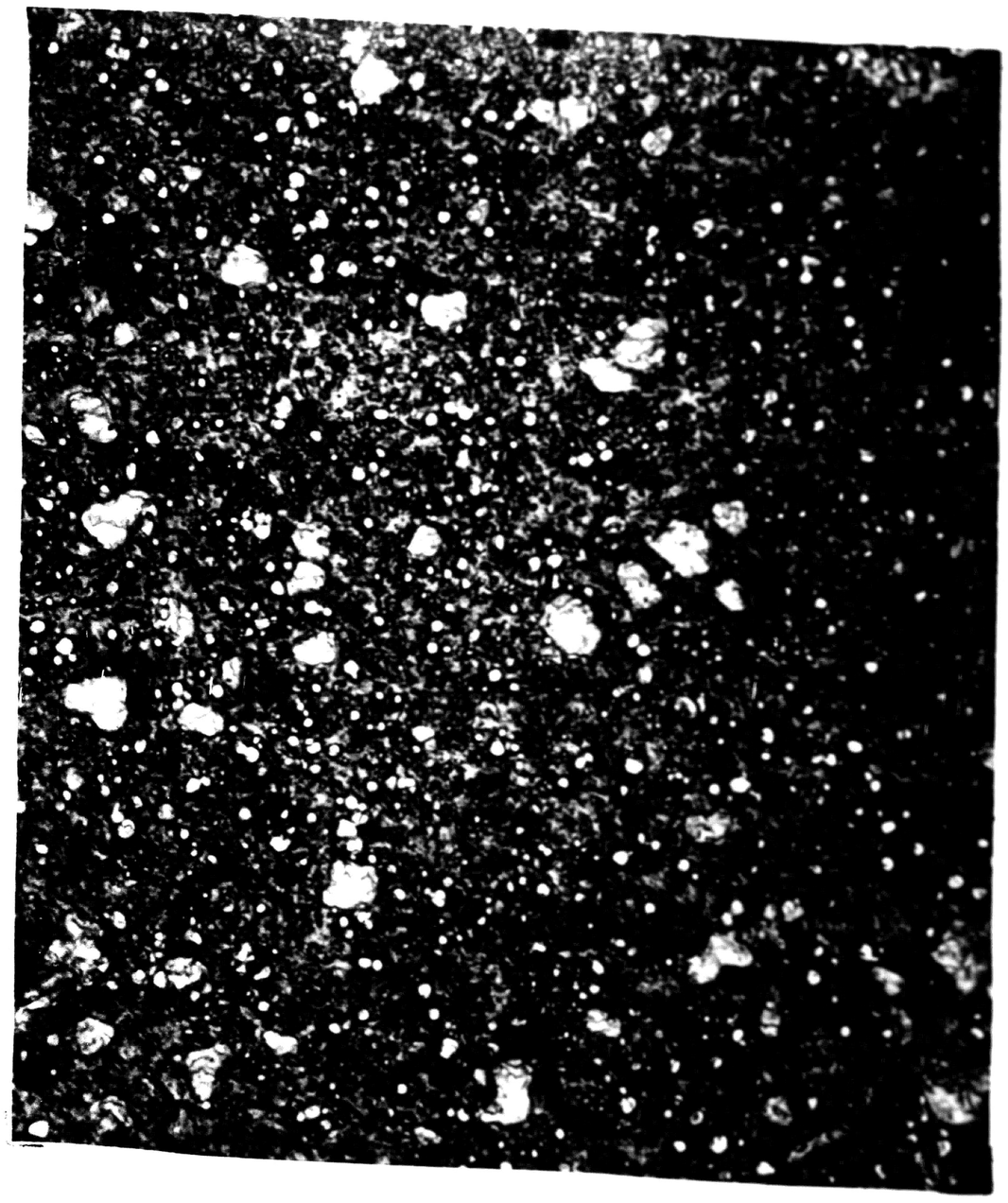
Micro structure photograph of
Tool C etched in nital solution

Magnification - 500X
Exposure time - 60 sec.



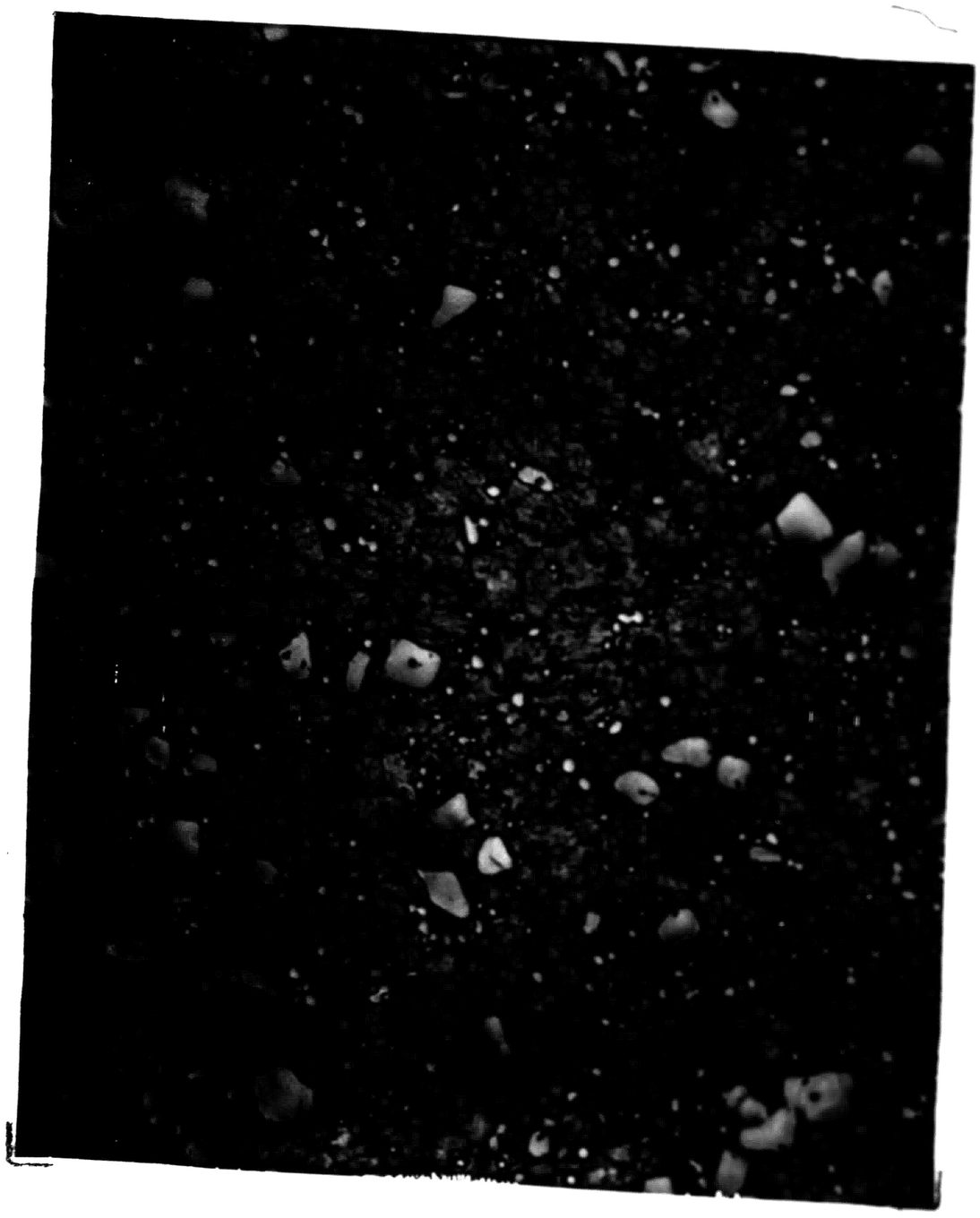
Micro structure photograph of
Tool D etched in nital solution

Magnification - 500X
Exposure time - 60 sec.



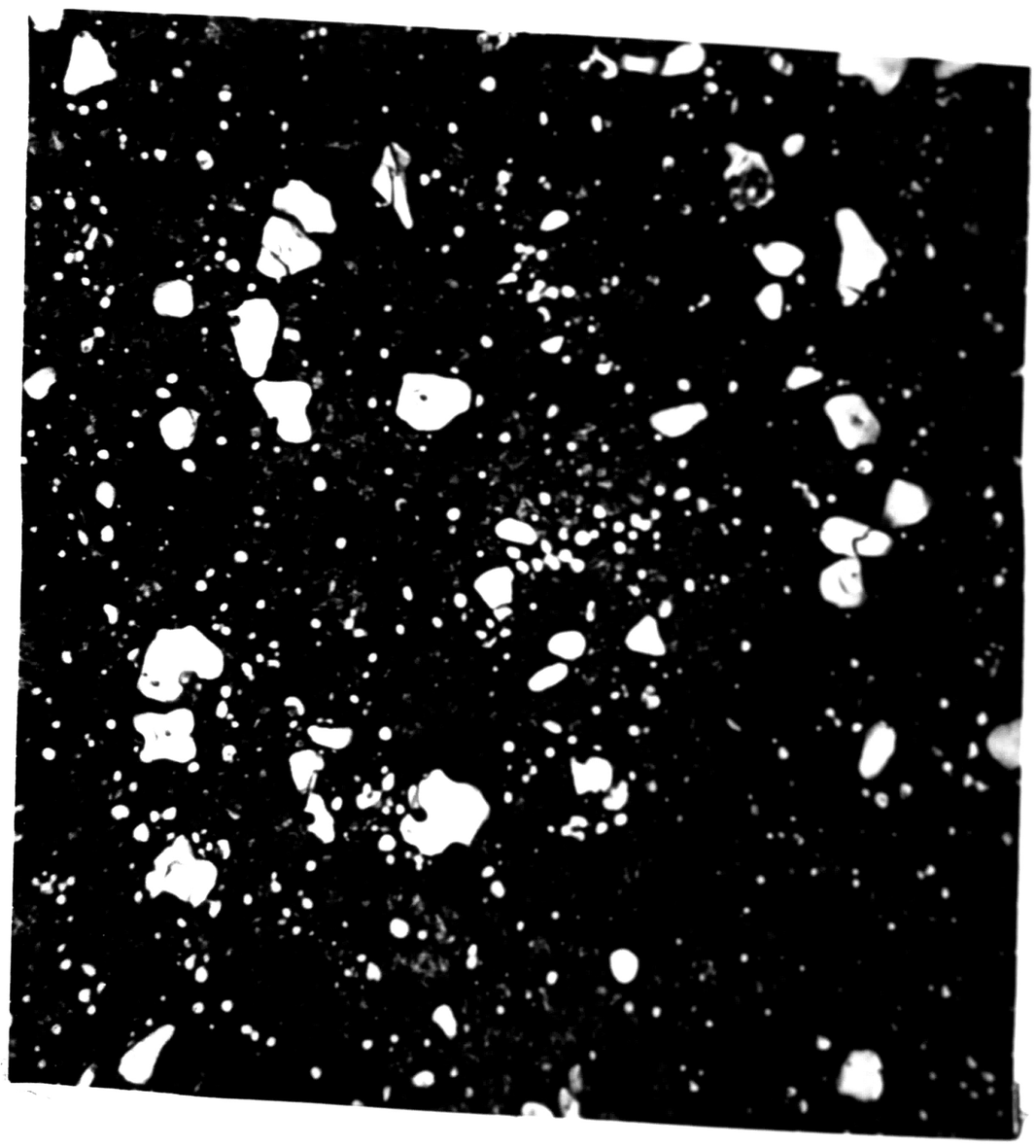
Micro structure photograph of
Tool E etched in nitol solution

Magnification - 500X
Exposure time - 60 sec.



Micro structure photograph of
Tool F etched in nitol solution.

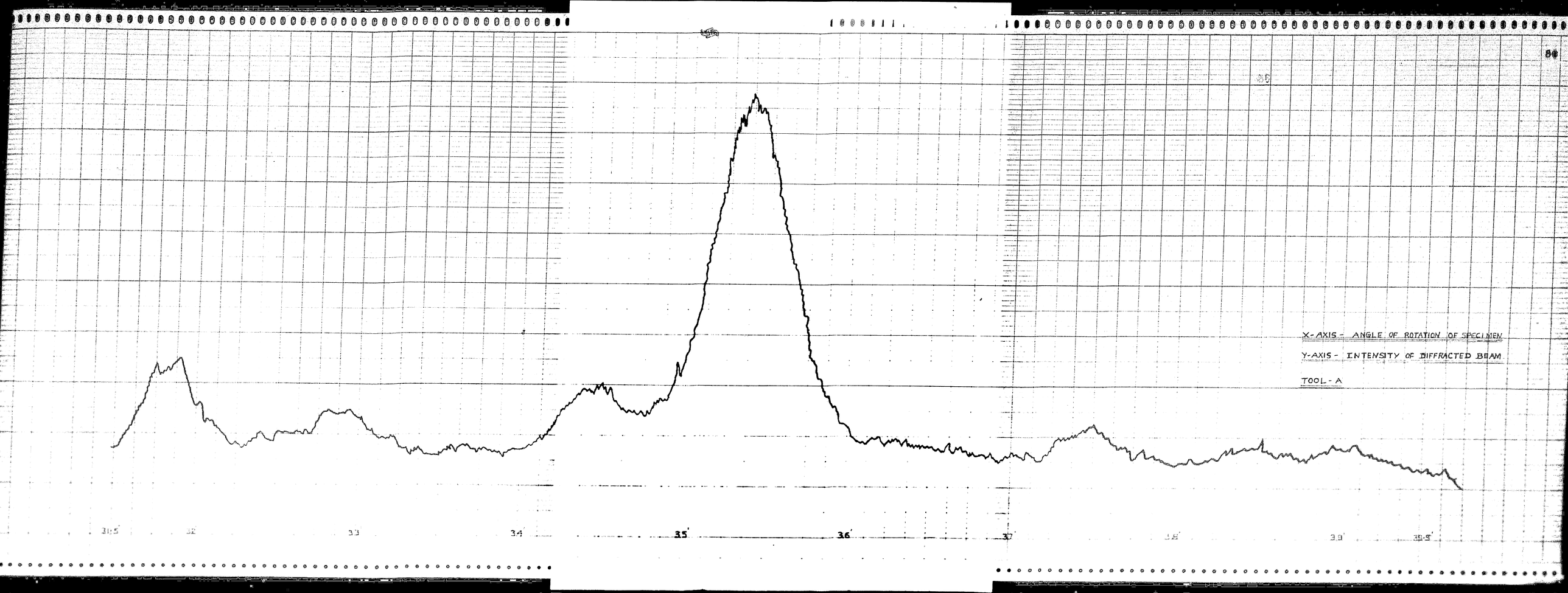
Magnification - 500X
Exposure time - 60 sec.

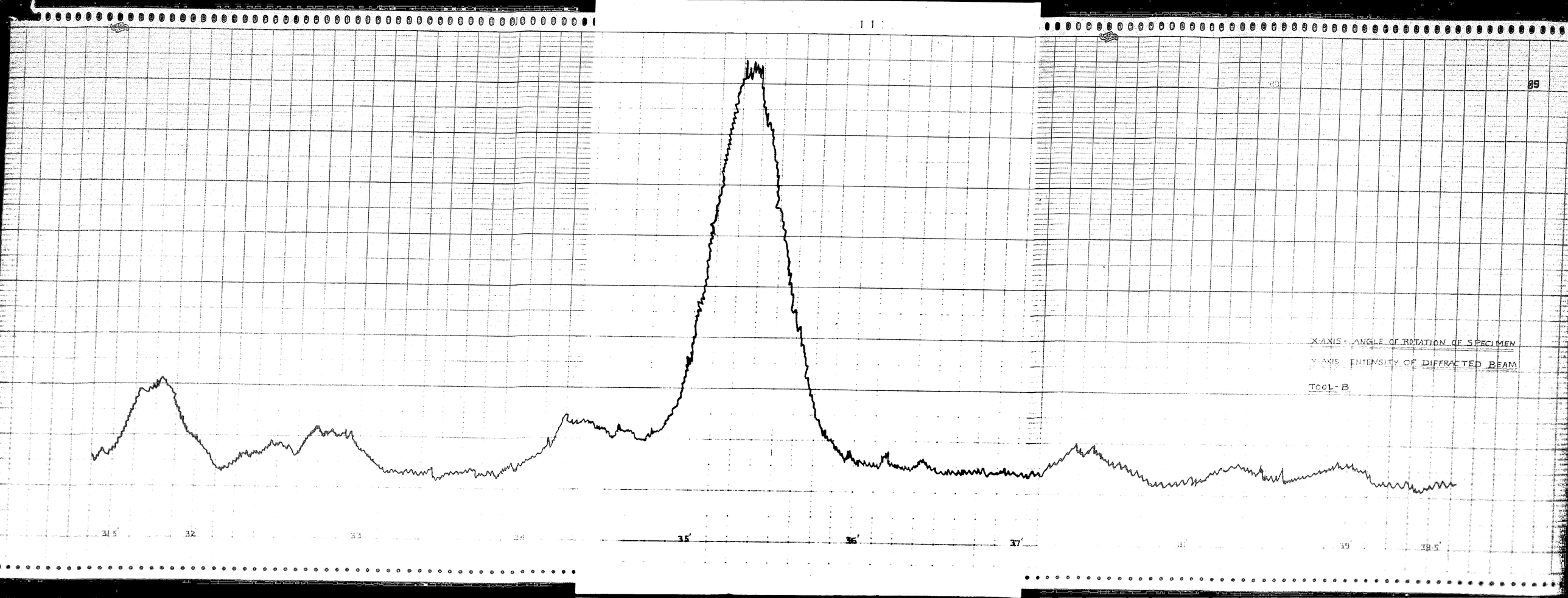


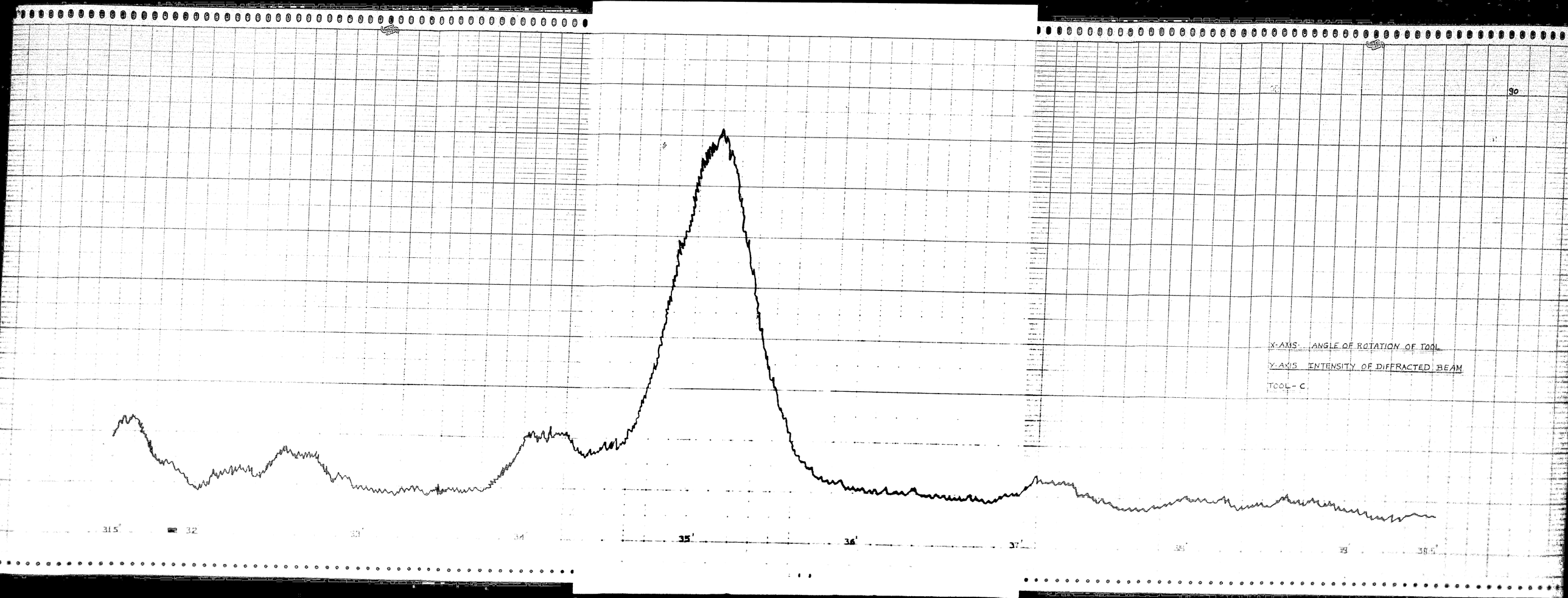
Micro structure photograph of
Tool C etched in nital solution

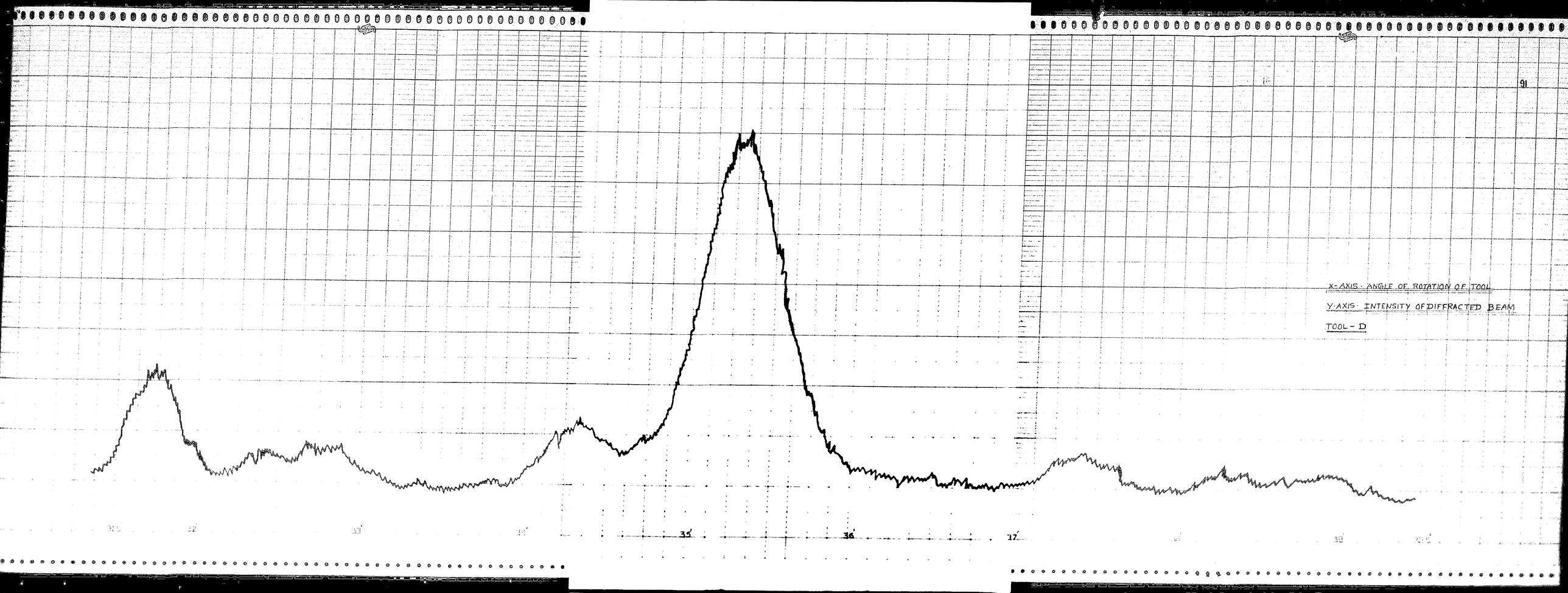
Magnification - 500X
Exposure time - 60 sec.

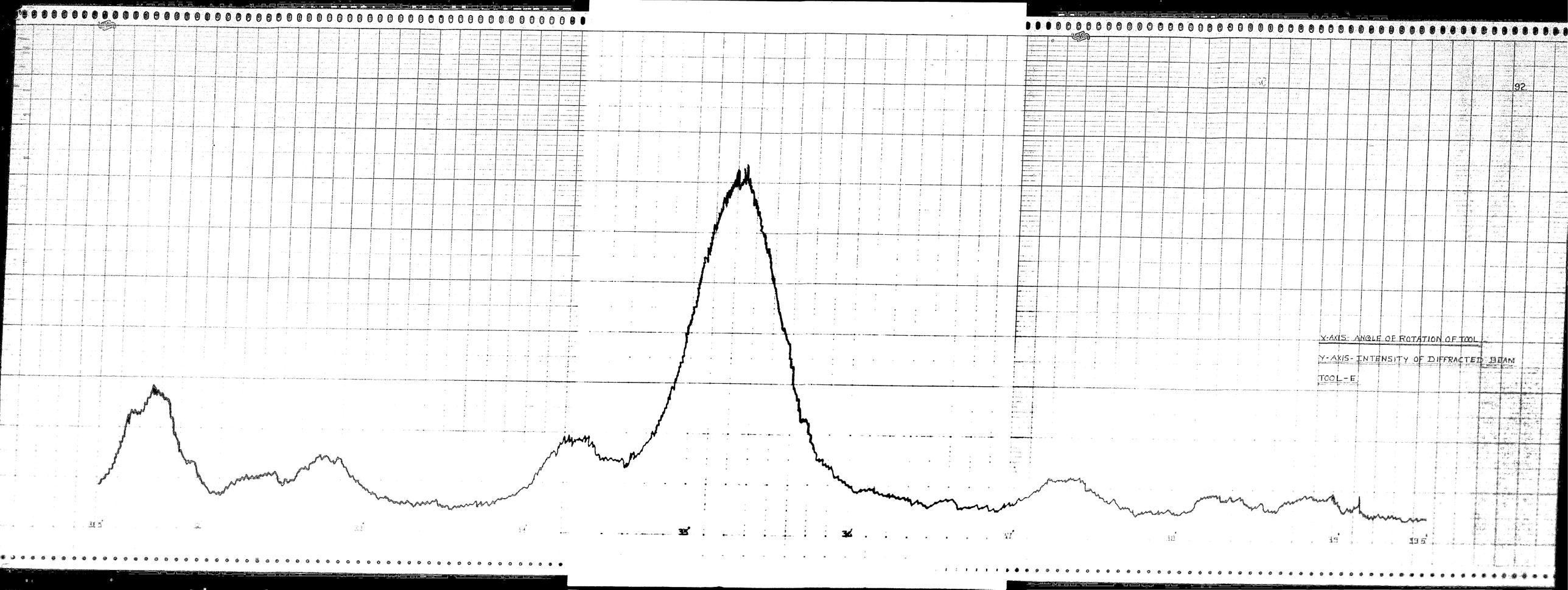
X-RAY DIFFRACTION CHARTS

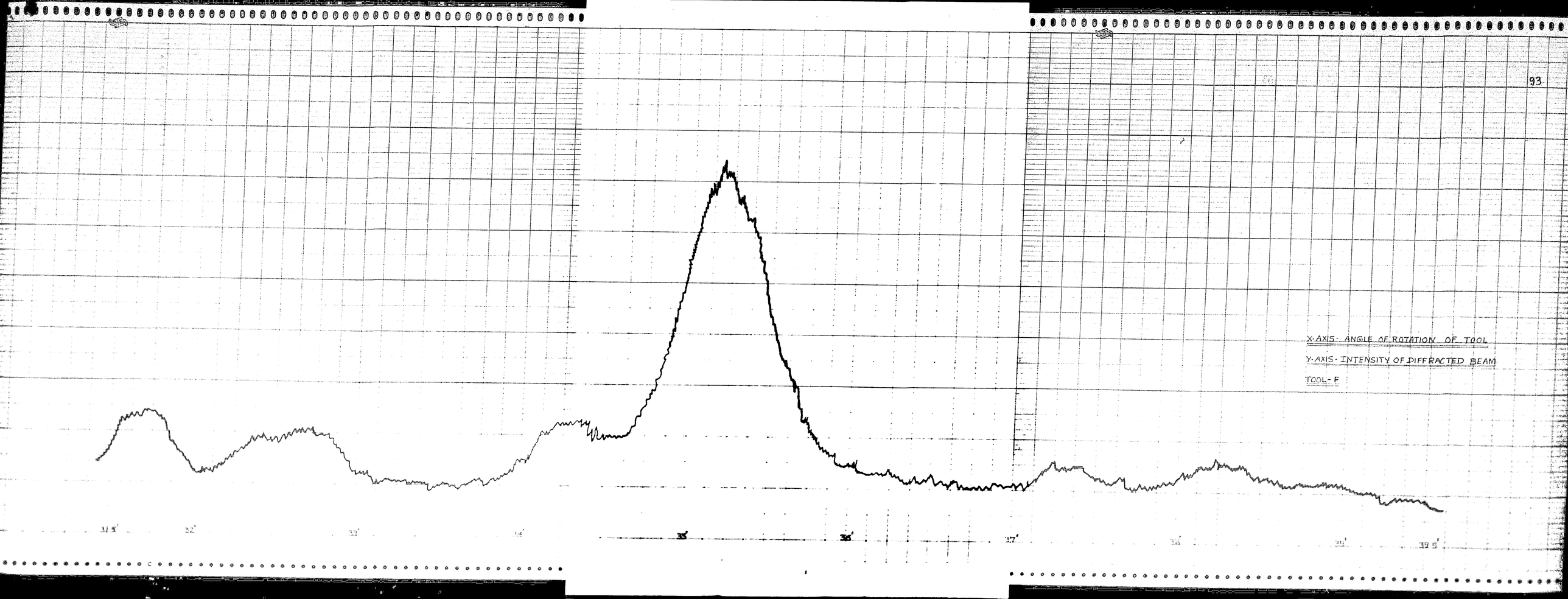

X-AXIS - ANGLE OF ROTATION OF SPECIMEN
Y-AXIS - INTENSITY OF DIFFRACTED BEAM
TOOL - A
30.5
32
33
34
35
36
37
38
39
39.5

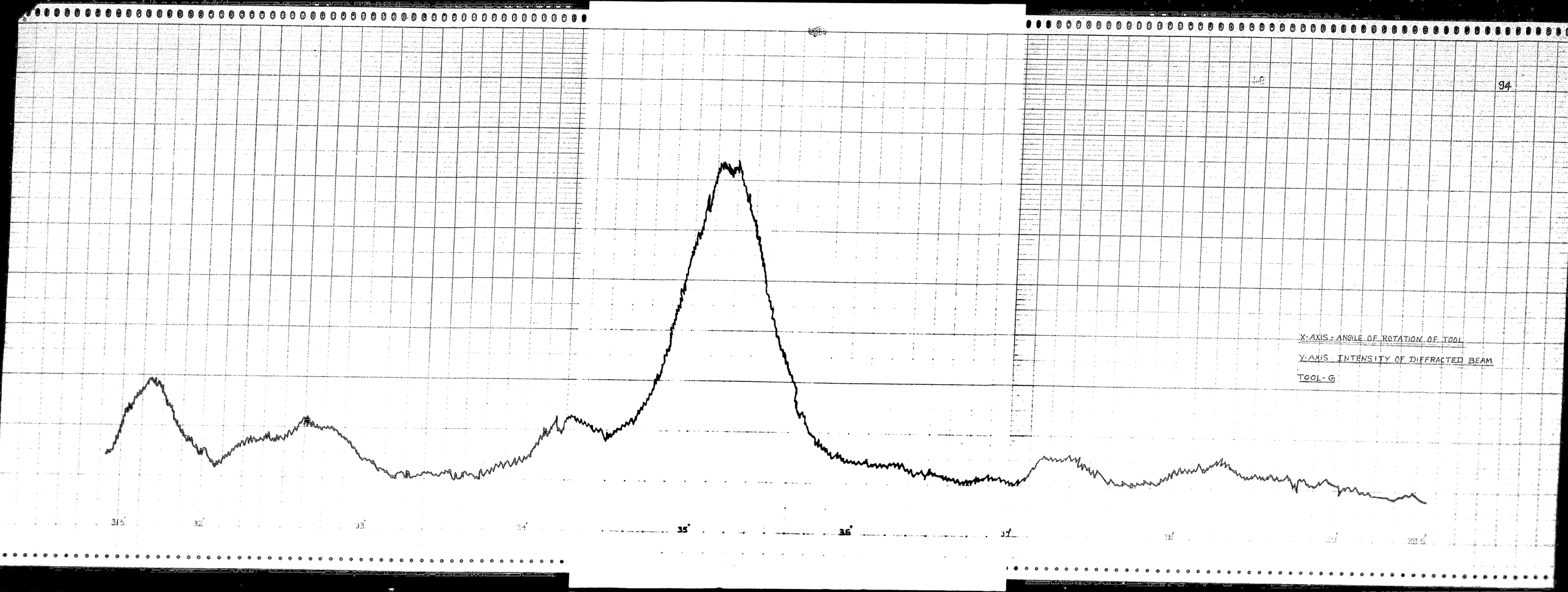

X AXIS - ANGLE OF ROTATION OF SPECIMEN
Y AXIS - INTENSITY OF DIFFRACTED BEAM
TOOL - B
31.5
32
33
34
35
36
37
38
38.5


X-AXIS ANGLE OF ROTATION OF TOOL
Y-AXIS INTENSITY OF DIFFRACTED BEAM
TOOL - C
315°
32
33
34
35°
36°
37°
38.5°


X-AXIS · ANGLE OF ROTATION OF TOOL
Y-AXIS · INTENSITY OF DIFFRACTED BEAM
TOOL - D
35
36
37


X-AXIS: ANGLE OF ROTATION OF TOOL
Y-AXIS- INTENSITY OF DIFFRACTED BEAM
TOOL-E


X-AXIS: ANGLE OF ROTATION OF TOOL
Y-AXIS: INTENSITY OF DIFFRACTED BEAM
TOOL - F
31.5°
32°
33°
34°
35°
36°
37°
38°
39°
39.5°


X-AXIS : ANGLE OF ROTATION OF TOOL
Y-AXIS INTENSITY OF DIFFRACTED BEAM
TOOL - G
31°
32°
33°
34°
35°
36°
37°

Computer Program

Analysis of Variance for Factorial Design

Problem No. 1

Number of Variables 5

Number of Replicates 2

Variable	No. of Levels
1	3
2	2
3	2
4	7
5	3

(3F6.3)

Grand Mean 1.32661

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
1	2	59.42090	29.71045
2	1	13.93441	13.93441
3	1	36.48017	36.48017
4	6	18.79353	3.13226
5	2	27.11909	13.55955
12	2	.27545	.13772
13	2	6.98810	3.49405
14	12	2.58515	.21543
15	4	2.86567	.71642
23	1	3.11473	3.11473
24	6	.68261	.11377
25	2	1.19345	.59673
34	6	1.47017	.24503
35	2	2.23916	1.11958
45	12	2.07215	.17268
123	2	.70124	.35062
124	12	.89982	.07499
125	4	1.14422	.28605
134	12	1.93188	.16099
135	4	2.61603	.65401
145	24	.90044	.03752
234	6	.68785	.11464
235	2	.22377	.11189
245	12	.64093	.05341
345	12	.78076	.06506

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
1234	12	.61758	.05146
1235	4	1.13776	.28444
1245	24	1.13541	.04731
1345	24	1.55985	.06499
2345	12	.22550	.01879
12345	24	1.47105	.06129
Within Replicates	252	5.85014	.02321

Vita

The author was born in Madras, India, on September 10, 1938, the son of Dr. R. Sankaran and S. Kalyani. He is married to Rajalakshmi and has a daughter, Nirmala.

He took his higher Secondary Certificate from P.S. High School in Madras in 1954. He entered the Government Arts College in 1954, and received the degree of Intermediate Science in April, 1956.

In 1956, he entered Vivekananda College, Madras, and took his Bachelor of Science (B.Sc.) degree in Physics which was conferred by the University of Madras in 1959.

Subsequently, he joined the Madras Institute of Technology where he completed requirements for the post-graduate diploma in Automobile Engineering, with a first class, in April, 1963.

In August, 1963, he joined the manufacturing operations of Massey Ferguson Tractors in Madras and successfully completed the two year engineering apprenticeship. He was an Assistant Engineer in the Production Engineering Department from June, 1965 to August, 1969, at which time he left for the United States to study for his M.S. in Industrial Engineering.

He has been a member of the Madras Production Council, Madras, India, and is a student member of the Society of Manufacturing Engineers of the United States.